Effect of Temperature upon the Properties of Metals

A Symposium

Held at a Joint Meeting, May 29, 1924,
at Cleveland, Ohio

OF

IE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
29 W. 39th St., New York, N. Y.

AND

HE AMERICAN SOCIETY FOR TESTING MATERIALS
1315 Spruce St., Philadelphia, Pa.

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SYMPOSIUM ON EFFECT OF TEMPERATURE UPON THE PROPERTIES OF METALS[1]

A REVIEW OF THE PRESENT STATE OF KNOWLEDGE OF THE PROPERTIES OF METALS AT VARIOUS TEMPERATURES AND A DISCUSSION OF THE NECESSITY FOR PROMOTING FURTHER KNOWLEDGE

FOREWORD

Greater economy and security in central-station development and in oil-refinery operations require the designing engineer to have an accurate knowledge of the properties of metals under stress at high temperatures. Lack of this knowledge gives rise to a critical situation and it is therefore timely that The American Society of Mechanical Engineers and the American Society for Testing Materials are joining in the presentation of the four papers that introduce this Symposium. These papers set forth the importance of having information available, discuss the difficulty of comparing tests that have already been made on metals at high temperatures, and review the knowledge now existing in regard to the properties of metals at high and low temperatures.

Some such topical discussion as will result from the presentation of these papers at Cleveland would sooner or later have been forced by the necessity for a cooperative attack on the problem of securing data to provide for the actual construction of central stations operating at high temperatures. This joint session, however, is the direct outcome of the activity of Sub-Committee No. 3 on Steel Flanges, Sectional Committee on the Standardization of Pipe Flanges and Fittings, organized under the procedure of the American Engineering Standards Committee. Interest in the subject was stimulated by the discussion on the paper presented at the 1922 Annual Meeting of the A.S.M.E. by G. A. Orrok and W. S. Morrison on the Commercial Economy of High Pressure and Superheat in the Central Station, and by the papers by Frederick N. Bushnell and Charles H. Merz before the meeting of the National Electric Light Association in June, 1923.

This joint session at the Cleveland Meeting of the A.S.M.E. is but the first step, and it is the earnest hope of the two Societies that out of the discussion of the papers in question there will evolve a

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[1] Held at a Joint Meeting of The American Society of Mechanical Engineers and the American Society for Testing Materials, May 29, 1924, Cleveland, Ohio.

definite program of cooperative standardization and research upon which the commercial uses of metals at high and low temperatures may be based. There is much work that may immediately be accomplished, such as:

1. Accumulation of existing unpublished data covering satisfactory and unsatisfactory service of various metals in different fields.
2. Standardizing procedure for testing materials at high and low temperatures. This should preferably include new comparative tests of metals by the principal methods now in use in various laboratories and likewise, a critical examination of data already published.
3. Outlining new research work to be done. The first and most important materials to be investigated are considered to be carbon and alloy steels, so-called "heat-resisting" alloys consisting of various combinations of nickel, chromium, iron, tungsten, molybdenum, etc., and trimming materials (chiefly alloys of nickel and copper) for valves and equipment intended for high-temperature service in power stations, oil refineries, etc.

To carry forward these three projects will require the wholehearted cooperation of the technical and industrial organizations interested.

The Symposium was arranged by the following committee, which acted in an advisory capacity to the Committees on Papers and Publications of the two Societies:

V. T. Malcolm, *Chairman*
H. J. French
W. F. Graham
R. S. MacPherran
L. W. Spring
A. E. White

The two Societies take this opportunity of expressing their appreciation of the services of this committee.

INDUSTRIAL APPLICATIONS OF METALS AT VARIOUS TEMPERATURES

By L. W. Spring[1]

About one hundred and fifty years ago James Watt improved Newcomen's "atmospheric" steam engine and went to the then "enormous" steam pressure of ten pounds per square inch, utilizing in addition the expansive force of steam as well as its direct pressure. From that time till now, though quite slowly, steam pressures have gone up and up, through 50, 100, 150, 200 and 250 lb. per sq. in. each with its increasing temperature, until of late years pressures of 350 lb. per sq. in. are more or less common. Though the superheating of steam before using was suggested by Watt it was not actually tried out by him and its use did not become at all common until within the last twenty years. In superheat practice the steam is given an additional 150 to 300° F. (85 to 170° C.) of temperature, obtained, of course, by passing the steam from contact with the water in the boiler into another chamber, or through superheater pipes. Here it is converted by the further heating into "dry" steam with the additional heat mentioned, having then a total temperature of from 550 to 750° F. (288 to 400° C.).

While the increases in pressures and temperatures during the approximately one-hundred-and-fifty-year period mentioned have been quite gradual, at the present time a seemingly rather drastic change is taking place which at first thought may appear to some to be very sudden, and possibly unwise, though it must be admitted that technical and mechanical talent have made wonderful strides within the last two decades. This change is the very decided increase in working steam pressures, which almost everywhere is occupying the thought of power plant designing engineers and which, in some cases, is already being translated into actual plant installation. Regular working pressures of 600 lb. per sq. in. are being or shortly will be used in two or three plants which are looking toward the greatest possible efficiency to be obtained with safety. Undoubtedly, increases in working pressures are not to stop here. Three or four power plant designers in this country already have arranged to try out, in a commercial way, in small units, steam at 1200 lb. working pressure. These have as antecedents a German experimental plant which operated at 900 lb.

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[1] Chief Chemist and Metallurgist, Crane Co., Chicago.

pressure for a period of nine months and a plant in Sweden, which, though built for 1500 lb., is now operating at 900 lb. per sq. in. In one installation in England the full critical steam pressure of 3200 lb. per sq. in. is to be tried shortly.

When generated freely from water, that is without pressure, steam occupies approximately seventeen hundred times the volume of the water it came from and has a specific gravity or density of about 0.0006. At the critical pressure of 3200 lb. per sq. in., however, and under a temperature of at least 706° F. (375° C.), it occupies only the equivalent of the volume of water from which it was generated and has, therefore, a specific gravity of approximately 1. In other words, under these conditions it has the same specific gravity as the water in the boiler and it is possible that the steam may be in and through the water or even below it in the boiler, since the two have the same density. The speculative possibilities and the promises of largely increased efficiencies by operating at 3200 lb. pressure and 750° F. (400° C.) are very interesting and have been quite thoroughly discussed elsewhere.

Without dwelling longer on the subject of pressures, which have been referred to mainly to indicate the rather extreme tendency toward higher efficiencies and therefore toward new designs and probably new materials in steam power practice, we will pass to the matter of temperatures.

As told above, present-day superheated steam practice has developed rapidly during the past twenty years with the result that a large number of power plants now use total operating temperatures of 550 to 750° F. (288 to 400° C.) A superheat of 315° F., that is, 750° F. (400° C.) total temperature, has been and is yet considered the tentative top limit of temperature for high-pressure power plant work. The reason for this is that metals which at present are available for steam generating purposes undergo considerable losses in strength as their temperatures rise above 600° F. (315° C.) Just where the point of recession begins and exactly where the curves of tensile strength, elastic limit, elongation and reduction of area lie with temperature increases, are matters upon which metallurgists are not yet quite fully agreed. Safety requires that we go slow in increasing operating temperatures above the 750° F. (400° C.) total temperature. How much this tentative maximum can be raised with safety eventually will depend in great measure upon agreement of results of metallurgists who are determining the strengths of materials to be used for power plant purposes and also upon more satisfactory materials which probably will be devised. While working pressures are being increased now by leaps and bounds, because these can be taken care of by increase in metal thickness, it is probable that increases of working temperatures will be much more slowly and cautiously made.

There is a second extensive use of this class of materials at high temperatures, and here working temperatures have considerably exceeded the 750° F. (400° C.) mark. This is the application of these metals: cast steel, malleable iron, and other boiler, piping and valve materials, to the oil refining industry. In the early days of petroleum refining it was chiefly the "coal oil" or kerosene which was utilized. There were at that time no internal combustion engines with their demand for the more volatile gasoline. Likewise there was little demand for petroleum lubricants, animal oils being considered the proper lubricants for machinery. With the expanding use of the automobile and the tractor, the demand for gasoline and the volatile portion of petroleum has outrun their production through straight distillation methods. Hence there have been made extensive efforts through high temperature or combined temperature and pressure "cracking" to increase the production of gasoline or a serviceable equivalent by such artificial breaking up of the less valuable, heavier petroleum oils. Without going into the history of their development it can be said that there are now somewhere around fifteen or twenty recognized "cracking" processes. These vary considerably in type of apparatus used and in the application of heat, the taking off, separation, and condensation of the vapors formed, as well as in pressures and temperatures used. In general, it may be said that the pressures are comparatively low, though there seems to be a trend toward the use of higher ones. The majority of these processes use pressures of around 100 lb. per sq. in. with temperatures of from 750 to 850° F. (400 to 450° C.). Three or four use 350 lb. pressure and 900° F. (480° C.), while one uses as high as 600 lb. pressure and 900° F. (480° C.). Pressures in the latter process probably surge as high as 750 lb. per sq. in., and temperatures may go as high as 950° F. (510° C.). Two such processes are utilizing as high as 1000° F. (540° C.) of temperature, with, however, only 350 lb. of pressure. While, apparently, there has been little or no trouble as to materials standing up so far as actual strength is concerned, even at these temperatures, anxiety naturally exists in the minds of both user and producer over consequences should any material containing flaws get into service. Furthermore, failures might occur through corrosion, breaking of parts under pipe strains, etc. Any failure is serious since the uncondensed vapors from the cracking stills are extremely inflammable and explosive.

As will be shown by the contributions of others to this program, losses in strength of cast steel at such high cracking temperatures as

900 and 1000° F. (480 to 540° C.) are rather great, considerably more so than at 750° F. (400° C.), the tentative top point for superheated steam service. However, under existing pressures and other service conditions, cast steel is serving well. Whether much will be gained by further increase in cracking temperatures and what further pressure increases may be made remains for the future to tell.

There are certain non-ferrous metals which are made use of in equipment for power plants and oil refineries. These are the metals or alloys of which steam turbine blades, valve seats, and sometimes other parts of valves are made. In general, valve-seat alloys contain as a base considerable percentages of nickel and copper. Under increased temperatures some of these alloys do not suffer more than cast steel, so far as strength is concerned. In addition to good strength under working conditions such alloys must have sufficient hardness to resist the cutting action of steam, scale or grit, for, to be satisfactory, valve seats must remain tight. Seating metals must have approximately the same coefficient of expansion under heat as that of the valve body and disk metal, and they should be as non-corrosive as possible, for corrosion also is an enemy to valve tightness. While considerable research is constantly going on, the ideal valve-seating material for high-pressure, high-temperature steam probably has not been found, and, certainly, the proper seating metal for oil-cracking vapor service is yet a matter of doubt.

While in the ferrous alloys the plain carbon steels have given satisfactory service so far and undoubtedly can be used safely at somewhat higher temperatures than are considered wise at present, it may be that alloy steels eventually will be found desirable.

Such alloys as chrome-nickel, chrome-iron-nickel, and others which are often used for carbonizing boxes, annealing pots, supports for articles in enameling ovens, floors and arches of furnaces, where temperatures of from 1600 to 2000° F. (870 to 1100° C.) prevail, are hardly within the scope of this paper. It is possible, however, that these indicate the trend toward other materials which may be necessary to keep pace with the demand for higher operating pressures and temperatures in various industrial applications.

METHODS OF TESTING AT VARIOUS TEMPERATURES AND THEIR LIMITATIONS

By V. T. Malcolm[1]

Introduction

In the design of apparatus for use at temperatures either above or below normal, it is of importance that the designer be familiar with the physical characteristics of the metals or alloys specified at the temperature to which they will be subjected in service. As many processes require the use of metals at temperatures other than normal, the degree of success of a metal or alloy must be measured by its stability under such working conditions. As a matter of fact, most failures at temperatures other than normal are due not to the quality of the metal or alloy but to the improper application of certain metals in connection with work for which they are entirely unsuited. For use at other than normal temperatures a careful study must be made of an alloy's characteristics, for with the advent of the central power station and oil refinery operating at great pressure and high temperature, failure of material in service is likely to be disastrous both to property and life.

At the Power Session(**190**)[2] of the annual meeting of the American Society of Mechanical Engineers held December 7, 1922, at New York City, a statement was made that power plant equipment had kept pace with the demand, except information regarding the properties of metals at elevated temperatures. Again at the Annual Convention(**195**) of the National Electric Light Association held June 4, 1923, New York City, it was claimed that while higher pressures were assured, higher temperatures must be provided for in metallurgy. In *Mechanical Engineering*(**211**), March, 1924, a résumé of power plant progress is given, and the author calls attention to the fact that the use of temperatures above 750° F. (400° C.) has not been contemplated owing to the lack of reliable information.

The importance of these statements to the mechanical engineer is profound, as he is directly responsible for the safety of the structures he designs, and he is probably unwilling to take for granted that a metal is suitable for other than normal temperatures without being convinced that tests have been carried out in a correct manner.

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[1] Metallurgist, The Chapman Valve Manufacturing Co., Indian Orchard, Mass.

[2] The bold face numbers in parentheses refer to the papers of the Bibliography appended hereto, page 124.

The testing of metals at temperatures other than normal is probably one of the most vital fields of engineering research to-day and will in the near future be one of the most actively exploited fields of metallurgy in the search of alloys, both ferrous and non-ferrous, to withstand temperatures other than normal. A most cursory examination of scientific and technical literature will convince anyone of the extent of scientific interest in this subject, and we believe it is one of the most serious problems confronting industries to-day.

The ultimate aim of all temperature tests should be to devise a comprehensive series of tests to which standard specimens of metals or alloys may be subjected and by which the relative physical properties of these metals may be predicted for certain service conditions. At this time anyone who undertakes a survey of the literature on the temperature problem is certain to be overwhelmed by the different types of furnaces, extensometers, strain gages, thermocouple location, etc., that have been used by the various investigators, and on the other hand numerous curves and data are shown, which are comparatively worthless to the designing engineer, unless the method of making tests and reaching thermal equilibrium are shown. Therefore, the problems at hand are of such importance that it becomes necessary to give statements on the apparatus used, method of testing, and manner of reaching thermal equilibrium.

It is with this idea in mind that an attempt has been made to review part of the literature with reference to tests of metals at various temperatures by investigators who are thoroughly familiar with their work, and it is hoped in this way to reach some definite plan by which the work of these men may be correlated and standardized apparatus, method of testing, etc., developed for use in all future tests.

HISTORICAL

In reviewing the literature on the testing of metals at various temperatures, it is well to go back to the beginning and carry the work forward to the present time in order to show the remarkable progress that has been made in methods of test in this branch of engineering research.

As early as 1828 Tremery and Proirier Saint-Brice(1) carried out a series of experiments on the tensile strength of wrought iron. In 1837 Sir William Fairbairn(2) made a number of experiments on cast iron at various temperatures. In 1837 research was carried on by a Committee, of The Franklin Institute(3), on the Effect of Temperature on Boiler Plate. In 1856 Fairbairn(4) carried out a series of experiments on rolled iron at various temperatures. In 1860 David Kirkaldy(5) of Glasgow, Scotland, carried out a number of interesting experiments on the value of iron and steel at various temperatures, especially investigating the action of frost upon the metals. William Brockbank(7) describes some very interesting experiments in determining the effect of cold upon cast iron. In 1863 a series of tests was conducted by the Royal Technological Institute of Stockholm(6), on the properties of irons and steels at various temperatures. In 1871 Peter Spence(8) carried out a number of investigations with cast iron at low temperatures. Jouroffsky(12) of St. Petersburg in 1879 conducted a number of tests on rails at low temperatures.

Between 1885 and 1905 a great deal of attention was given the subject of testing metals at various temperatures by such well-known investigators as Rosenhain and Humfrey(74, 93), LeChatelier(39), Martens(18), Bach(44, 50), Unwin(16), Hopkinson and Rogers(55), Rudeloff(20, 36, 64), Stribeck(48, 52), Howard(17), Charpy(21, 25), Carpenter(24), and Hadfield(54) and quite numerous articles appeared in the German and British engineering literature. Very little work was done in the United States during this period with the exception of the work of Howard.

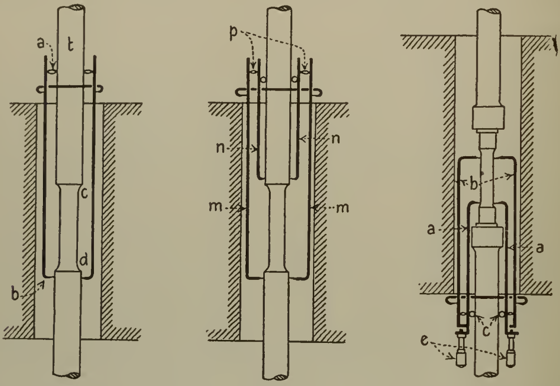
The modern line of investigation was begun about 1912 and is still being carried on to the present day by such investigators as Huntington(85), Bengough(82), Hansen(101), Dewrance(98), Aitchison(123), Lea(187), Dickenson(173), Dupuy(150), in England and France, and in this country by such men as Meyers(128), Spring(83, 216), Jeffries(127), Sykes(163), Merica(168), McNiff(144), French(153, 179), Spooner(162), MacPherran(158), Langenberg(200, 201), Epps and Jones(116), Perrine and Spencer(104), Priester and Harder(206), White and Upthegrove(147), Speller(215), d'Arcambal(148) and the author(188, 189, 203, 212).

EARLY METHODS OF TESTING

The old methods used for testing metals at various temperatures consisted of heating a specimen in a furnace or forge or freezing it in some liquid medium, transferring it to a testing machine and quickly conducting the test at normal temperature, allowing for loss or gain of heat in transferring test bars and in conducting the test. In some cases the temperature was merely judged by the oxide film on the specimen and in other cases by the use of thermometers. These methods were of course very crude and the results unreliable, but as this was before the day of our modern equipment the tests served their purposes.

In 1888 a most extensive series of tests was made by Howard(17) at the Watertown Arsenal, and as this was also before the day of the electric furnace and the pyrometer the specimens were heated by a series of Bunsen gas burners and the temperature estimated from the coefficient of expansion of the heated specimen. No temperature correction for the coefficient of expansion was used. These tests received and still receive quite an amount of favorable comment.

In 1890 Martens(18) published his investigations on the tensile properties of iron, steel and copper at elevated temperatures. He used a bath of paraffin for temperatures up to 400° F. (200° C.) and a bath of lead or lead-tin alloy for temperatures from 400 to 1100° F. (200 to 600° C.) The gas jets were located on the sides in conjunction with a vertical testing machine. For measuring temperatures he used in the former case a mercury thermometer and in the latter case an air thermometer. For determination of the elastic limit he adapted his mirror extensometer shown in Fig. 1. The test piece was turned down in the center at *c d* and the extensometer clips were attached at *b* on the lower enlarged end and were carried out of the furnace, for the attachment of the measuring rhombs *a*. The extension, therefore, was measured on the length *a b* and correction was made for the extension of the enlarged ends, in order to obtain the extension of the gage length, *c d*.



(*a*) Marten's Arrangement.

(*b*) Rudeloff's Arrangement.

(*c*) National Physical Laboratory Arrangement.

FIG. 1.—Diagrams of High-Temperature Extensometers.

Unwin(16) in 1889 published results of tests of metals at elevated temperatures. These tests were carried out by heating the specimens in an oil bath from below by gas burners, the whole apparatus being placed between the jaws of a testing machine as shown in Fig. 2. Thermometers were used to measure the temperature. Charpy(25) in 1896 also used a bath with burners located below. LeChatelier(39) used a horizontal testing machine with gas jets located above. Batson(80) used steam coils in the testing of 50-ft. lengths of copper wire up to temperatures of 140° F. (60° C.). Stribeck(48, 52) used a cylindrical oven, electrically heated, through which the bar passed. Other investigators used methods more or less similar, the main features

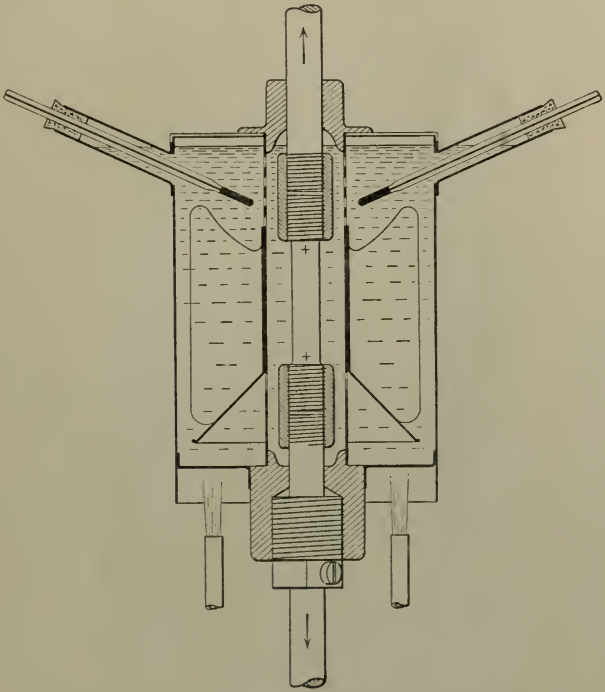


FIG. 2.—Diagram of Testing Apparatus Used by Unwin.

being air, gas or liquid baths heated by blast lamps, Bunsen burners, or electric current, and in the case of low temperature a freezing solution.

In nearly all the early investigations we find that temperatures were taken at points distant from the test specimen itself, the assumption being that temperature of bath and test bar must be alike.

It is therefore our conclusion that most of the early investigations can be only approximate determinations at best.

MODERN METHODS OF TENSION TESTING

During the past ten years methods of furnace construction, location of the thermocouple, calibration of pyrometer, and the general checking up of the work in hand has received close attention and great accuracy has been attained, so that at this time conclusive results have been arrived at and industrial applications certainly may be based on these findings.

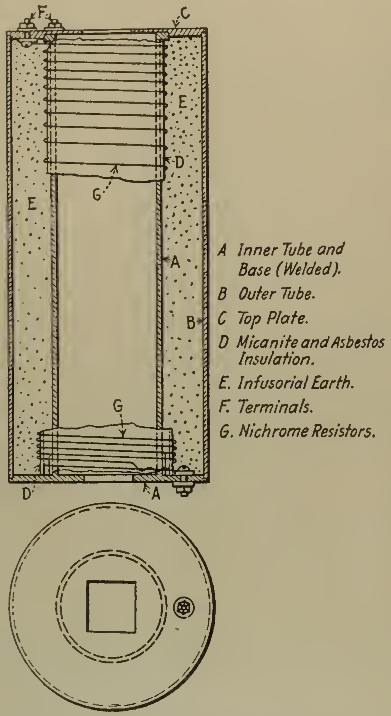


FIG. 3.—Electric Furnace Used by French in High-Temperature Tests.

The apparatus and methods of test of some of the more prominent investigators during the past ten years will be described in detail. Attention will first be devoted to tension tests, after which reference will be made to other tests of metals at various temperatures.

H. J. FRENCH (153, 179)

Furnace.—The test specimens are heated by means of an electric furnace shown in Fig. 3. Two spiral resisters in series are used: one covers the entire length of the inner tube (11 in.) and the other is concentrated at the ends, the two requiring about 80 ft. of No. 22 nichrome wire. Yokes and the greater part of the test bar and rods are contained in the heating chamber, which is 11 in. long. The furnace is operated on either 110 or 220-volt direct current, close regulation being obtained by a variable resistance in series in the circuit.

Proportional Limit Apparatus.—The apparatus used in the determination of the limit of proportionality at various temperatures,

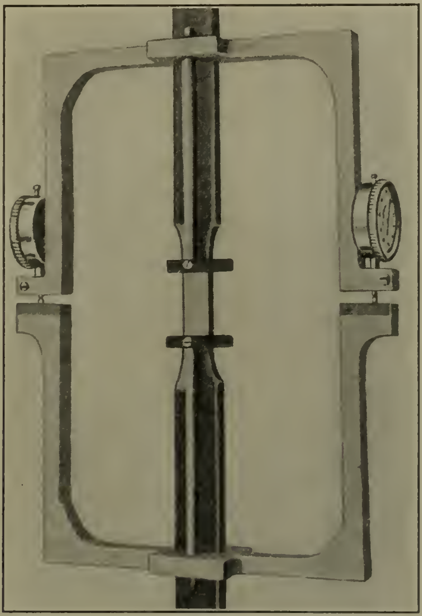


FIG. 4.—Apparatus Used by French for Determining Proportional Limit.

illustrated in Fig. 4, consists primarily of two aluminum-alloy frames each rigidly fastened to a quenched-and-tempered steel yoke by two annealed low-carbon steel rods. The specimen passes freely through holes in the base of each of the frames. Yokes are clamped to the specimen by three quenched-and-tempered high-speed steel screws, while the spreading of the former is overcome by the long screw. The flanges on the upper frame are so arranged that dial micrometers for indicating deformation may readily be securely fastened to them, while those of the lower frame are capped with polished steel plates in order to give a smooth bearing surface to the plungers of the dials.

The smallest division on the instruments used is equal to 0.001 in., but estimated readings to the nearest 0.0001 in. are readily obtained.

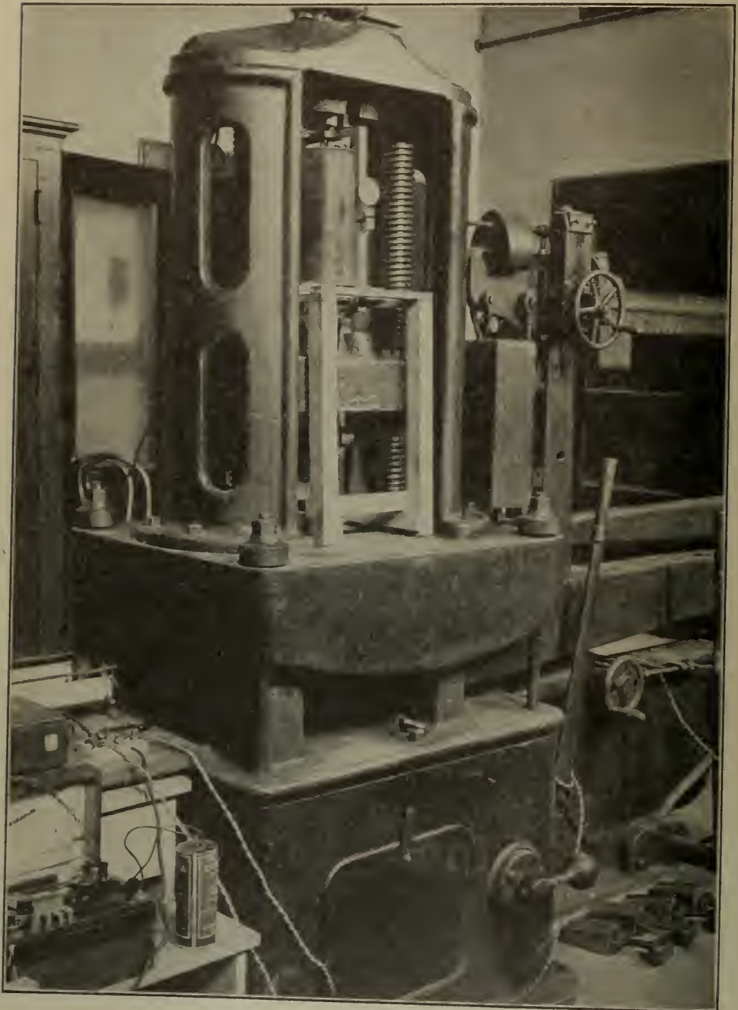


FIG. 5.—Assembled Apparatus Used by French for Determining the Tensile Properties of Metals at High Temperatures.

When stress is applied to the specimen, one-half the algebraic sum of the deformation recorded by the two dials represents the deformation of the specimen, which is centrally located with respect to the entire apparatus.

Test Procedure.—The method of setting up the apparatus together with the procedure followed in actually carrying out the tests is substantially as follows: A specimen is marked on the surface with a double-pointed center punch leaving marks 2 in. apart. The yokes are attached to the specimen by setting the single screw into the impressions. Then by lightly tapping the opposite side of the yoke containing the two screws, a light impression of their exact location on the test bar is obtained. These points are then enlarged by use of the double-pointed center punch, and the yokes carrying rods and frames are firmly attached to the test piece. Bolts holding the upper frame to the two rods are next taken off and the upper frame removed.

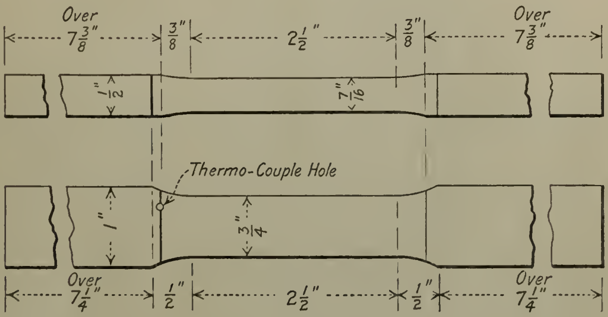


FIG. 6.—Form and Dimensions of Test Specimen Used by French.

The specimen is then passed up through the furnace until the rods appear above the top, when the upper frame is again fastened to the rods. After the furnace is placed on the stand and the specimen is in the jaws of the testing machine the dials are attached to frame and adjusted to zero. The completely assembled apparatus is shown in Fig. 5.

When thermal equilibrium at the desired temperature is reached, an initial load of about 1500 lb. is applied and the dials read or, as a matter of convenience, set at 17.2. Readings are then taken at increments of 500 or 1000 lb. actual load until the proportional limit is passed. The dials are then removed and the specimen is broken in the usual manner with a low rate of extension which approximates the intermittent increases of stress applied during determination of the limit of proportionality. Tests at each temperature are made in duplicate or triplicate and the proportional limit is obtained from the stress-strain diagram.

The temperature is measured by a No. 22 standardized chromel-alumel couple connected to a Leeds and Northrup portable potentiometer. The end of the couple is inserted directly into a small hole drilled in the specimen at the fillet, its exact location being shown in Fig. 6.

Thermal Equilibrium.—In order to obtain reliable and satisfactory results with the method described in the preceding paragraphs, thermal equilibrium must be reached prior to the start of the loading and maintained during the actual 8 to 15 minutes during which the test is being carried out. The adjustable resistance in series in the electrical circuit makes current adjustment possible, so that the loss of heat from the heating unit, ends of test specimen and auxiliary apparatus by radiation, convection, and conduction balances the energy added to this entire system. The effect of temperature variations may be large unless care is taken to allow sufficient time for the specimen to become uniformly heated throughout after the potentiometer has once indicated the desired temperature. The dial readings will assist in determining when equilibrium has been reached and is being maintained.

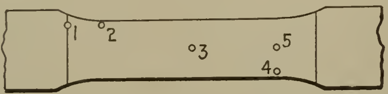


FIG. 7.—Temperatures at Various Parts of Test Specimen.

Desired Temperature		Temperature of Specimen at Points Indicated										Time after Couple No. 1 First Reached Desired Temperature, minutes	Average Temperature of Couples Nos. 2, 3, 4, and 5		Maximum Temperature Variation	
		Point No. 1		Point No. 2		Point No. 3		Point No. 4		Point No. 5						
deg. Fahr.	deg. Cent.	deg. Fahr.	deg. Cent.	deg. Fahr.	deg. Cent.	deg. Fahr.	deg. Cent.	deg. Fahr.	deg. Cent.	deg. Fahr.	deg. Cent.		deg. Fahr.	deg. Cent.	deg. Fahr.	deg. Cent.
329	165	329	165	343	173	333	167	316	158	329	165	15	299	166	27	15
608	320	608	320	621	327	621	327	590	310	612	322	0	580	322	31	17
		617	325	633	334	633	334	608	320	644	329	5	592	329	25	14
		617	325	637	336	633	334	604	318	630	332	20	594	330	29	16
752	400	756	402	779	415	774	412	739	393	756	402	10	729	405	40	22
		756	402	779	415	774	412	739	393	756	402	20	729	405	40	22

Temperature determinations under actual test conditions, made by placing thermocouples in holes located at various points in the specimen carrying the entire auxiliary apparatus, show that the position chosen for the single thermocouple (in the fillet) is representative of about the mean gradient throughout the gage length, where the temperature gradually decreased from top to bottom. Fig. 7 shows a partial reproduction of these variations, which are within 45° F. (30° C.). It is the greatest in the upper temperature ranges under consideration, and does not exceed 36° F. (20° C.) at the lower temperature used. However, as the thermocouple, specimen with auxiliary apparatus, and furnace are in the same relative position in each test, the results obtained at various temperatures throughout the range, 70 to 870° F. (20 to 465° C.), are comparable.

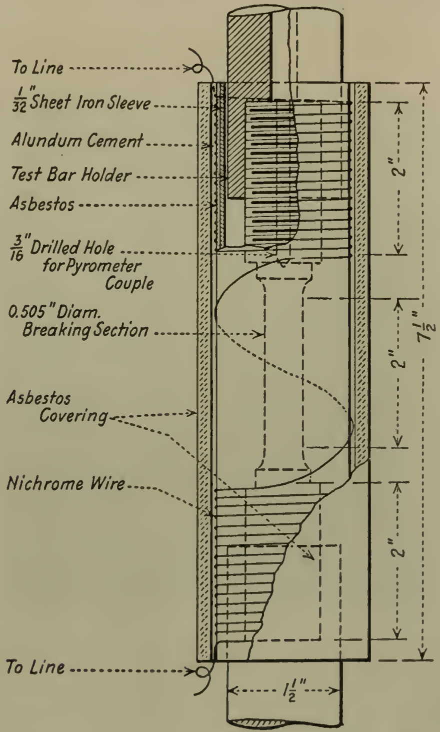


FIG. 8.—Heating Coil and Test Specimen Used by Bregowsky and Spring.

I. M. BREGOWSKY AND L. W. SPRING(83, 216)

Furnace and Testing Apparatus.—The heating apparatus consists of a $7\frac{1}{2}$ by $1\frac{9}{16}$-in. sleeve of $\frac{1}{32}$-in. sheet iron wrapped with one layer of $\frac{1}{16}$-in. sheet asbestos for insulation, and wound with twenty turns on each end with No. 18 or No. 20 chromel wire, leaving a gap of 3 in. in the middle, except for the approximate one-half turn connection between the end windings. The wire is plastered thinly with alundum cement to prevent excessive oxidation at high temperatures. Outside layers of sheet asbestos, shrunk on, insulate the wires and retain the heat. The coil, test bar and hole drilled in it for the thermocouple are illustrated in Fig. 8. Test bars are turned to 0.505 in. in diameter over breaking section and the ends are threaded to fit the self-centering holders of the testing machine. In the top end of the bar a $\frac{3}{16}$-in. hole is drilled axially to within about $\frac{3}{8}$ in. of the turned-down breaking section. In testing, the coil is suspended from the upper holder. The test bar, heating coil and self-centering holders into which the threaded ends of test bars screw are heat-insulated from the testing machine by $\frac{1}{2}$-in. pads of asbestos, bolted between steel flanges which form parts of the self-centering holders. The general assembly of the apparatus showing insulating flanges, heating coil, extensometer and pyrometer is given in Fig. 9.

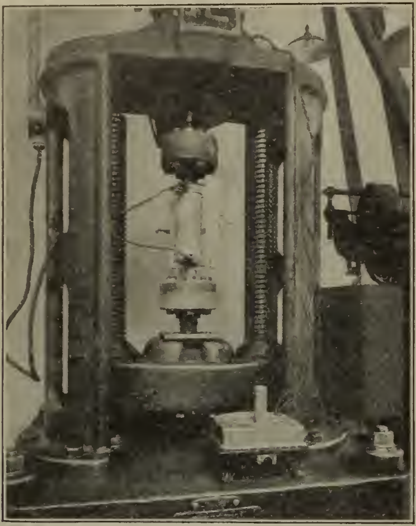


FIG. 9.—Testing Machine Used by Bregowsky and Spring with Test Specimen, Heating Coil and Temperature-Measuring Apparatus in Place.

In the hole in the top end of the bar a thermocouple is inserted, which gives the temperature inside the bar very near the turned-down breaking section. By careful regulation, any desired temperature between 70 and 1200° F. (21 and 650° C.) can be obtained in 20 minutes to 1½ hours and held without more than a few degrees fluctuation. Readings for proportional limit and yield point with the aid of an extensometer attached to the bar holders and breaking the bar (all of which requires four or five minutes) are accomplished within a few degrees of the desired temperature. Temperatures are taken with chromel-alumel couples, carefully standardized against the freezing points of chemically pure tin, zinc and aluminum. Measurements were read on a millivoltmeter.

On various occasions tests were made to determine variation of temperature of test specimens at several internal and external points, using for this purpose specimens drilled axially nearly to the lower end. The thermocouple inserted in the drilled hole was raised or lowered from time to time and readings were taken at various locations inside the bar. When using coils wound over their full length it was found practically impossible to avoid a higher temperature in the center or breaking section of the test bar than at the ends. Part of this variation is attributed to conduction of heat away from the ends of the test bar through the bar holders. Therefore, coils were developed wound on the ends only, and by throwing all the heat upon the ends of the test bar and none along its middle or heating section a quite uniform temperature in the breaking section and adjacent parts was obtained, the variations not exceeding 35° F. at 1200° F. (20°C. at 650° C.).

Tests were made to determine the accuracy of taking temperatures on the surface of the bar, by strapping the tip of another thermocouple to the outside of the drilled test bar at the middle of the breaking section and taking comparative readings after thermal equilibrium had been attained. Of course, these tests showed that temperature readings taken at the surface are somewhat higher than readings taken inside and it is believed that an "outside" thermocouple gets direct radiant heat from the heating coil and therefore registers higher. Moreover, even without direct radiant heat and assuming that the thermocouple registers the temperature of the outer fibers of the bar perfectly, the outer fibers naturally have a higher temperature than the center of the bar, because the heat goes from the surface toward the center.

G. C. PRIESTER AND O. E. HARDER(206)

In order to make tests at elevated temperatures a special apparatus as shown in Fig. 10 was developed. The temperature of the specimen is measured by a carefully calibrated thermocouple, the hot junction of which is clamped in contact with the lower shoulder of the specimen.

The specimen is gradually heated to the desired temperature by means of an electric furnace and is held at this temperature for 30 minutes to establish thermal equilibrium. Under these conditions it is believed that any heat changes that take place during the heating of the specimen are negligible. It is believed that there can be no question about the accuracy of the temperature measurements made in this way.

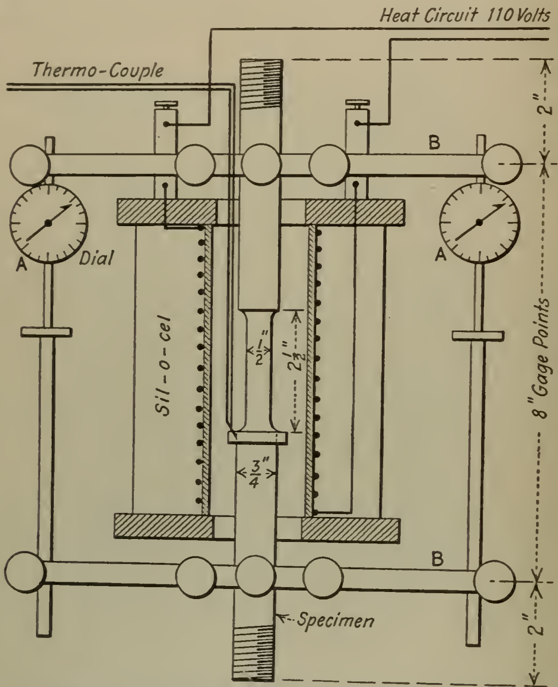


FIG. 10.—Sketch of Apparatus of Priester and Harder for Mechanical Tests at Elevated Temperatures.

Ames dial gages attached to yokes are used. The test pieces are heated to the required temperature in the furnace for one-half hour before testing.

A. P. SPOONER(162)

Specimens are heated in a circular electric furnace, with a thermocouple inserted against the middle of the pull section and connected with a Leeds and Northrup recording pyrometer. The thermocouple is wired to the necked-down section of the specimen and asbestos packing used to close the ends of the furnace tube, which is $1\frac{1}{2}$ in. in diameter. All specimens were held at the testing temperature for 30 minutes before the load was applied. The apparatus is illustrated in Fig. 11.

The specimens are pulled in a 100,000-lb. Emery testing machine. The yield point is determined by the drop of the beam and occasionally checked up with the dividers.

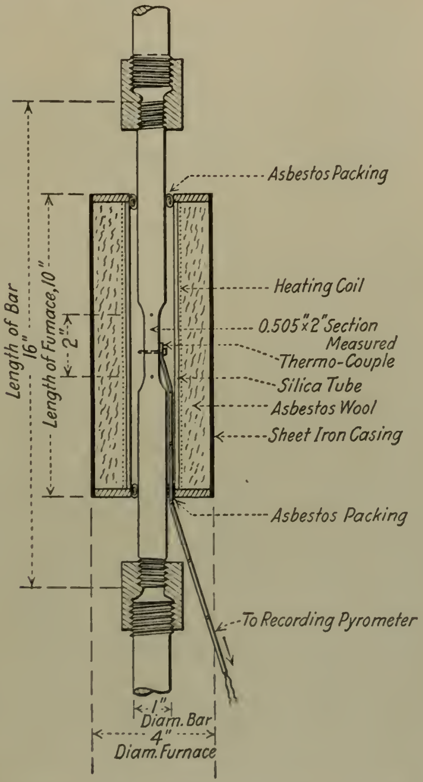


FIG. 11.—Arrangement of Test Specimen in Furnace used by Spooner.

An interesting feature to be noted in the tests reported by Spooner is the fracture of the broken test bars at the different temperatures. The usual commercial, structural and carbon steel fractures look very much alike, but with the addition of certain percentages of nickel, chromium and tungsten the colors of the fractured bars change considerably.

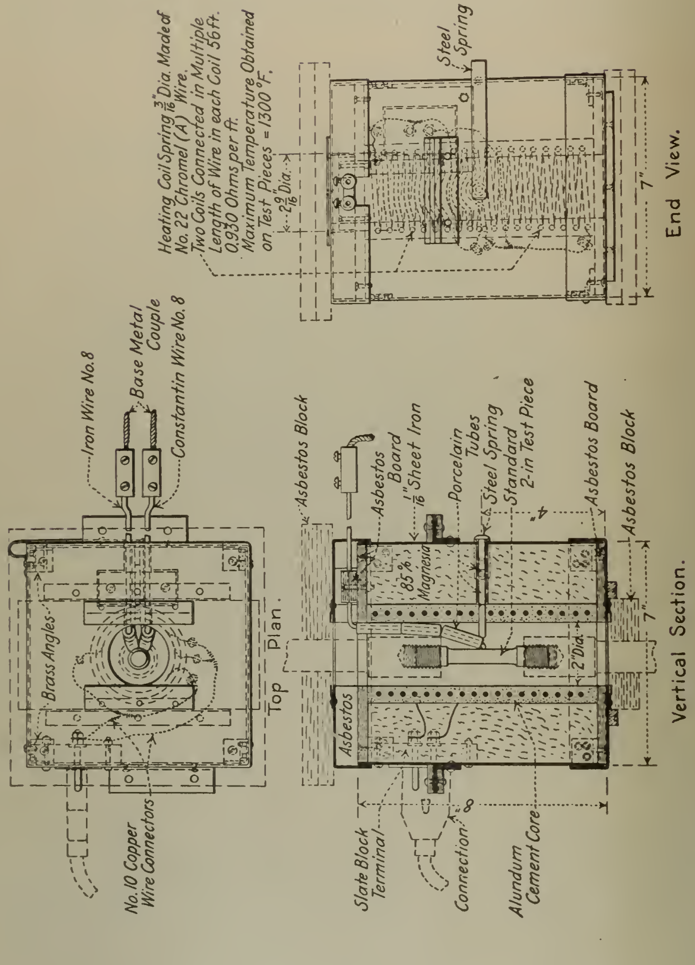


FIG. 12.—Diagram of Electric Heater Used by MacPherran, Showing Specimen in Position

R. S. MACPHERRAN (158)

The furnace used is a heating box 7 in. square by 9 in. high. The hole in which the test specimen is inserted is 2 in. in diameter and is lined with a core of alundum cement wound with No. 22 chromel wire. This wire is wound in two coils, one over the top and one over the lower half of the alundum core. They are connected in multiple. The coils are first covered with alundum cement and then with magnesia. The thermocouple enters at the top of the box and runs down in such a position that the point is opposite the center of the test specimen. A spring on the outside of the box forces a porcelain rod through a hole against the base metal couple, holding the point against the test specimen. The temperature is measured with a Leeds and Northrup pyrometer using a base metal thermocouple. The apparatus is illustrated in Fig. 12.

The specimens used are the standard 0.505-in. test bars with threaded ends. All tests are held at constant temperature from 15 to 30 minutes before pulling. The proportional limit was not measured but the yield point was determined by the drop of the beam, and above 600° F. (315° C.) it was uncertain.

MacPherran states there are two ways to determine the temperature in testing metals at elevated temperatures: one with the thermocouple in contact with the outside of the specimen at the center of its gage length and the other by inserting it in the specimen outside the gage length. If the thermocouple is in contact with the surface of the specimen at the center, the test specimen cannot be hotter than the couple. If it is inserted in the specimen outside the gage length the couple cannot be hotter than the specimen. The possible error of the first method is to get temperature readings that are too high and of the second method to get readings that are too low. After carefully considering both methods the former was selected. It is possible that the higher temperatures found by several investigators are due to the placing of the thermocouple. It would seem, however, that there is more to be said in favor of the system adopted than for the one requiring the insertion of the thermocouple junction in the test specimen. It is very difficult to maintain a constant temperature for a considerable distance in the furnace tube, and it is believed by MacPherran that the temperature should be taken as near as possible to the point of rupture.

A series of tests were made with one thermocouple touching the outside of the center of the test specimen as in the regular tests, and another couple adjusted so that the point was in the exact center of a hole drilled through the specimen in the same horizontal plane as the point of the first couple. To protect the point of this second couple, the hole was then plugged with asbestos. The two couples therefore indicated the temperatures at the surface and center of the test specimen. To emphasize the difference between center and outside, a test

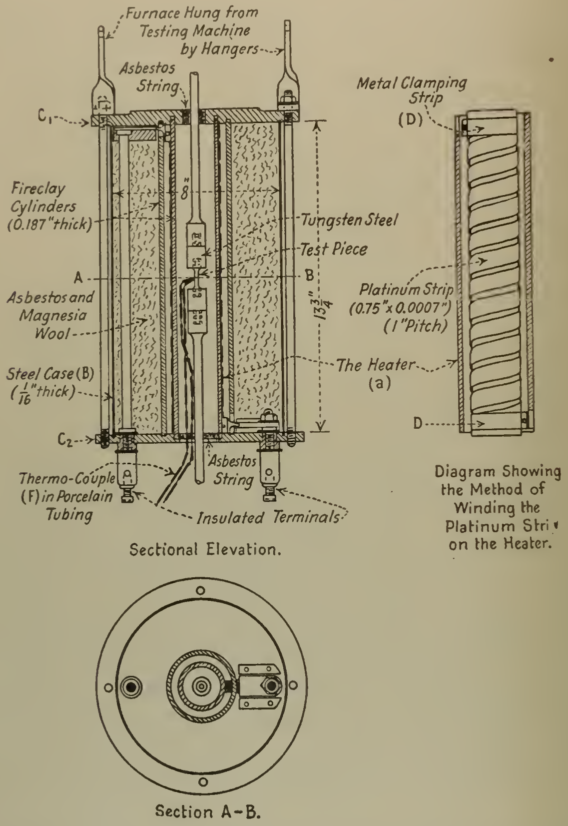
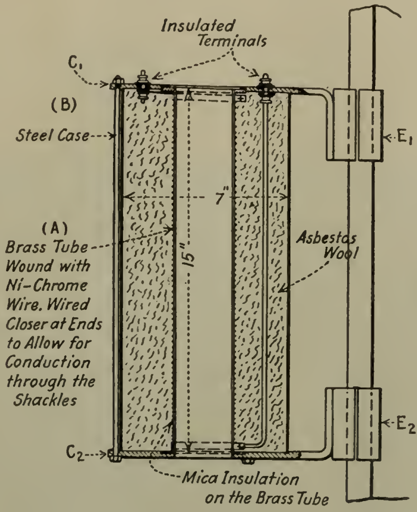
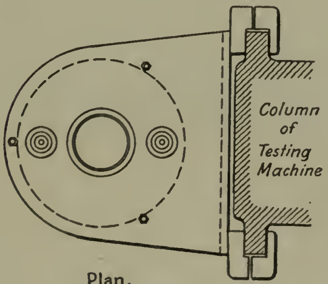


FIG. 13.—Platinum High-Temperature Furnace of the National Physical Laboratory for Tension Tests.

specimen 0.75 in. in diameter was used in place of the regular 0.505-in. diameter bar. Three sets of readings were taken at temperatures in excess of 500° F. (260° C.) with the result that the center of test specimen was found to be 22 to 36° F. (12 to 20° C.) below the temperature of the outside of the bar. With the 0.505-in. bar this difference would of course be less. As the area represented by the outer layers is much greater than that represented by the center, MacPherran believes that the central outside thermocouple location as used in these tests gives a better indication of average temperature of the specimen under test.



Sectional Elevation.



Plan.

FIG. 14.—National Physical Laboratory Furnace for Tension Tests up to 990° F. (600° C.).

NATIONAL PHYSICAL LABORATORY(169)

In the work of the National Physical Laboratory in England, two types of furnace were used in connection with a vertical testing machine.

A platinum furnace, Fig. 13, was used for temperatures up to 2200° F. (1200° C.), the heating element consisting of a platinum strip 0.75 in. by 0.0007 in. and wound on a fire-clay cylinder with an outside diameter of $\frac{2}{25}$ in., a thickness of 0.187 in. and a length $13\frac{7}{8}$ in. The ends of the strips are clamped in position on the cylinder by metal clips. A steel case surrounds the heater, and the space between the two is packed with asbestos and magnesia wool. The whole apparatus is clamped between two end plates on one of which two insulated terminals are fixed, these being connected to the two ends of the platinum heating coil. The furnace itself is suspended from the top shackle of the testing machine and uses a current of 15 amperes and 105 volts.

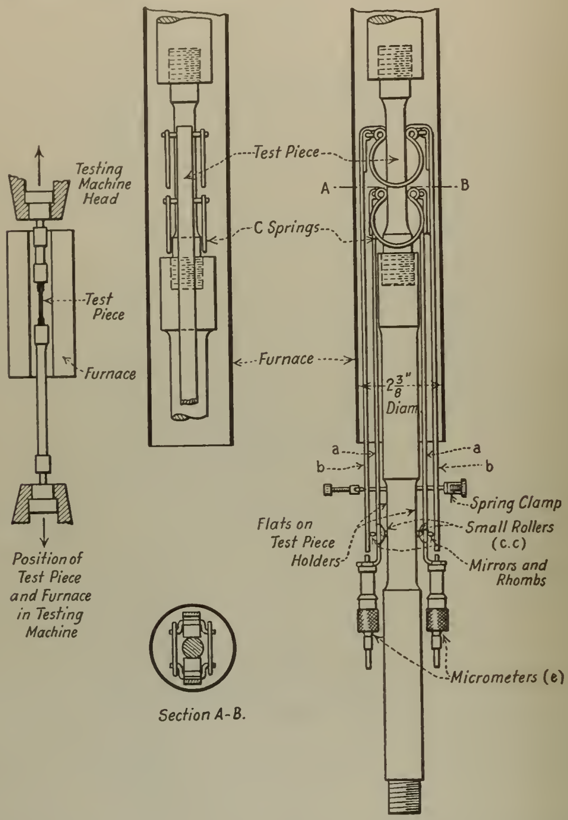


FIG. 15.—National Physical Laboratory High-Temperature Extensometer.

The second furnace used is for temperatures up to 1100° F. (600° C.) and is shown in Fig. 14. The heating element consists of nichrome wire wound on a brass tube. The tube is bound with mica, before winding the wire, in order to insulate it, and asbestos string is wrapped over the wire so as to keep the wire in position when it expands with the temperature. The heating chamber is surrounded by a steel shell 7 in. in diameter and the space between the shell and heating element is filled with asbestos wool. Two steel plates are bolted together clamping the heater and outer shell between them, and are arranged to connect the furnace to the frame of the testing machine. The ends of the heating coil are connected to two insulated terminals on the top plate. No. 18 nichrome wire is used for the heating element. The wire is coiled closer to the ends to allow for conduction of heat through the grips of the testing machine and to give a more uniform heating over the central three to five inches of the furnace. The temperature is measured with a thermocouple placed at the outside middle section of the gage length and protected by a porcelain tube.

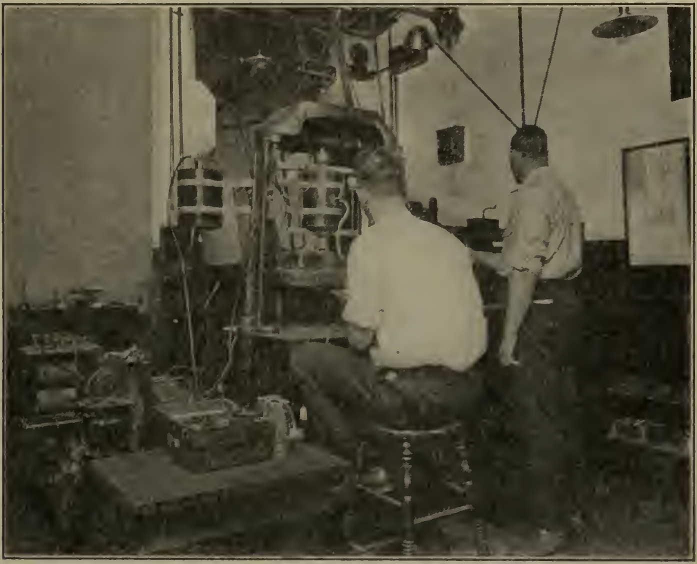


FIG. 16.—Apparatus Used by Malcolm in Tension Tests at High Temperatures, Showing Furnaces, Transformers, Potentiometer and Elastic Limit Apparatus.

The extensometer used is a combination of the best features of both Rudeloff's and Lea's extensometer and had two micrometers for measuring extension beyond the elastic limit. The clips are attached to the reduced part of the test piece by springs and protrude from the furnace. The inner clips are guided on flats on the test piece holders by small rollers. Mirrors and rhombs are placed between the clips and the whole is clamped together by a special spring attached to notches on the outer clip. The extension of test pieces causes relative movement of the clips and therefore rotation of the mirror rhombs which is measured in the usual way by a telescope and scale. The relative movement of the clips is also measured by two micrometers attached to the inner clips and working against the outer ones. Sketches of these extensometers are shown in Figs. 1 and 15.

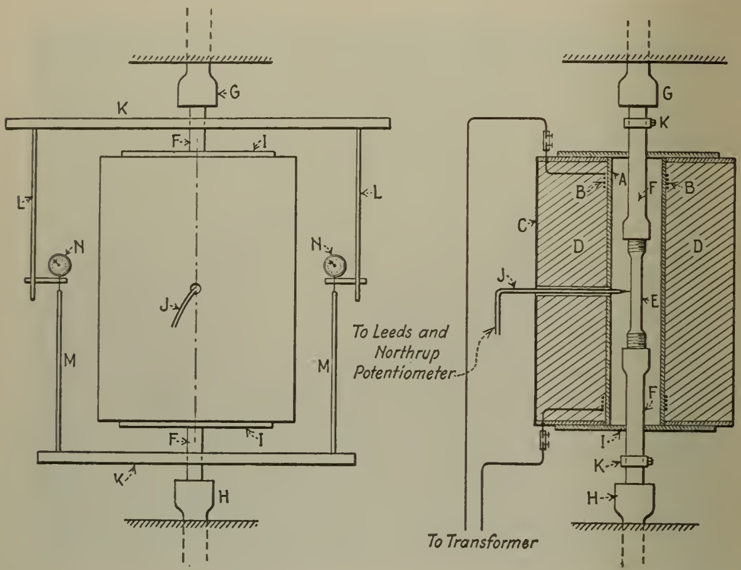


Fig. 17.—Diagram of Apparatus Used by Malcolm in Tension Tests at High Temperatures, Showing Specimen in Place and Location of Thermocouple.

V. T. MALCOLM(188, 189, 203, 212)

The tension tests of metals at elevated temperatures are made on a 100,000-lb. standard Olsen testing machine.

Pyrometers.—The pyrometer equipment consists of a portable Leeds and Northrup indicating potentiometer and thermocouples of 0.025-in. (No. 22) alumel and chromel wire.

Furnace.—The furnace equipment was made in duplicate in order to facilitate the heating and testing of specimens. The furnaces are attached to the outer leg of the testing machine by hinges so that they swing alternately into place between the heads for testing purposes. The general arrangement of apparatus is shown in Fig. 16, and Fig. 17 shows a section of the furnace with specimen in place and with extensometer gages attached and pyrometer inserted.

The test bars used are machined in the form of the standard 2-in. screw-end tension specimen 0.505 in. in diameter as shown in Fig. 18. In addition, special bars were used for calibration tests for each of the various metals tested, and were also used for certain temperature explorations and calibrations of the furnace. (See Fig. 19.)

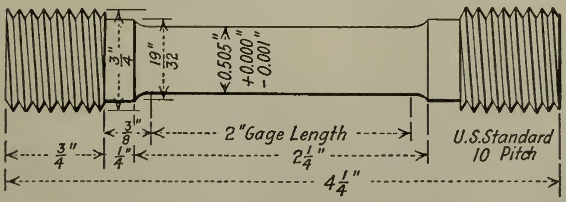


Fig. 18.—Test Specimen Used by Malcolm in High-Temperature Tests.

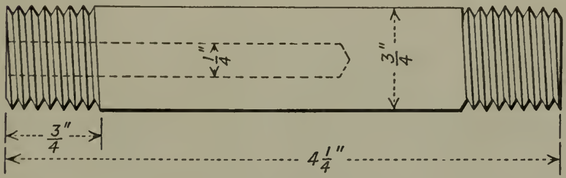


Fig. 19.—Calibration Bar Used by Malcolm in High-Temperature Tests.

In Fig. 17, *A* is an alundum tube upon which is wound the heating element *B*. This heating element is connected to the secondary of a transformer. The tube *A* is held in the container *C* and the space between *D* is filled with kieselguhr. The specimen under test, *E*, screws into the specimen holders *F*, which in turn screw into the testing machine adaptors *G* and *H*. *G* is the fixed member and *H* the moving member. When the specimen is in position, the doors *I* are closed and the thermocouple *J* placed against the test specimen at its mid-point. The doors *I* are made of asbestos board and fit snugly around the holders *F* so that no air currents can get into the heating chamber. As a further precaution against air currents, asbestos rope is wound around the holders *F* just inside the doors *I*. Arms *K* are rigidly fastened to specimen holders *F*. The rods *L* are fastened to the upper arm *K* and rods *M* to the lower arm *K*. Ames dial gages are connected to the fixed rods *L* and rest on the moving rods *M*.

Method of Test.—The test specimen is inserted in the heating unit and fixtures described. After the specimen has been at the desired temperature for at least one-half hour, an initial load of 100 lb. is applied in order to eliminate all lost motion. The Ames gages are then set at zero after which equal increments of load are applied and simultaneous readings of gages recorded. The size of the increment applied depends upon the kind of material under test and varies from 100 to 500 lb. Observations of elongation per increment of load are recorded until the yield point is passed. The Johnson elastic limit is then determined from a curve drawn through points obtained by plotting the elongation per increment of load.

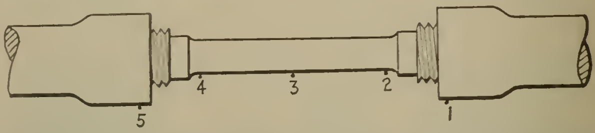


FIG. 20.—Sketch Showing Temperatures at Various Points of Test Specimen in Tests by Malcolm.

TEMPERATURES OF SPECIMENS AT POINTS INDICATED

Point No. 1		Point No. 2		Point No. 3		Point No. 4		Point No. 5	
deg. Fahr.	deg. Cent.	deg. Fahr.	deg. Cent.	deg. Fahr.	deg. Cent.	deg. Fahr.	deg. Cent.	deg. Fahr.	deg. Cent.
295	146	330	166	365	185	308	153	273	134
508	264	547	286	600	315	521	272	477	247
677	358	738	392	791	422	717	381	636	336
877	469	938	503	991	532	921	494	832	444

DIFFERENCES IN TEMPERATURE AT POINTS INDICATED FROM THAT AT POINT 3

Point No. 1		Point No. 2		Point No. 3		Point No. 4		Point No. 5	
deg. Fahr.	deg. Cent.	deg. Fahr.	deg. Cent.	deg. Fahr.	deg. Cent.	deg. Fahr.	deg. Cent.	deg. Fahr.	deg. Cent.
−70	−39	−35	−19	0	0	−57	−32	−92	−51
−92	−50	−53	−29	0	0	−79	−44	−123	−68
−114	−63	−53	−29	0	0	−74	−41	−155	−86
−114	−63	−53	−29	0	0	−70	−39	−159	−88

General Discussion of Accuracy of Test Results.—The accuracy of the results obtained in testing metals at elevated temperatures depends upon (1) the rate at which the load is applied, (2) the length of time the specimen is held under load at a given temperature, (3) the accuracy of the thermocouple and (4) the true temperature of the material under test. These points will be considered in order.

1. In general it may be said that the faster the rate of load application, the higher the tensile properties. In the author's tests a slow rate was used in order to observe the deformations which were plotted to determine the elastic limit. In this respect, the values reported are on the low side as compared with values at ordinary testing speeds.

2. The tensile properties decrease with the length of time the specimen is held under load at a given temperature. This may be dismissed from consideration inasmuch as all specimens were tested in approximately the same length of time—which was short.

3. In order to determine the accuracy of the thermocouples, the following procedure was adopted: One of the thermocouples used was checked against a standard and was found to be correct within experimental error. All other thermocouples used were then checked against this one and found to be within the limits of experimental error.

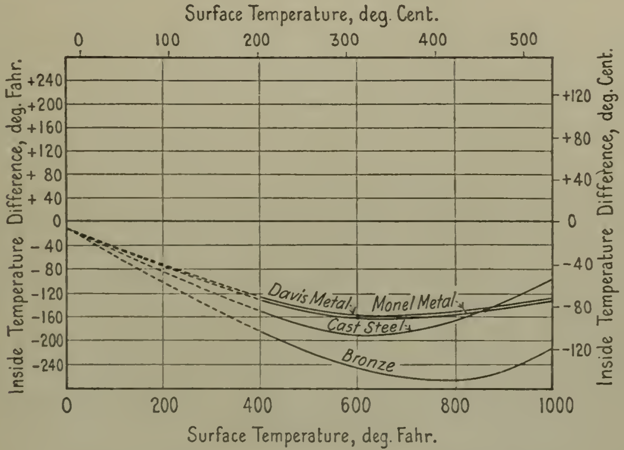


FIG. 21.—Malcolm's Temperature Calibration Chart.

4. The fourth point, regarding the true temperature of the bars, appears simple on its face, but after some of its phases are considered it is found to be very complex. The temperature of a specimen itself may vary in two ways: (*a*) From point to point along the surface and (*b*) from the surface to the center. The variation in temperature along the surface is easily determined by fastening the thermocouples to the points whose temperature is desired. The temperature of three points along the surface of the pull section of the specimen have been determined, namely, at the top fillet, at the mid-point, and at the bottom fillet. The results are shown in Fig. 20.

In order to determine the difference in temperature between surface and center of this specimen, a set of test bars known as calibration specimens were used. These bars were $\frac{3}{4}$ in. in outside diameter, with a $\frac{1}{4}$-in. hole bored from one end to $\frac{1}{2}$ in. beyond the center. This gave a wall thickness of $\frac{1}{4}$ in., equivalent to one-half the diameter of the standard $\frac{1}{2}$-in. bar. A thermocouple was placed against the outside, as was done in the regular tests, and another couple inserted in the longitudinal hole, both registering the temperature at the same section with $\frac{1}{4}$ in. of metal between. The whole apparatus was placed in the testing machine under the same conditions that obtained during the regular tests and comparative observations made from room temperature to 1000° F. (540° C.) The temperature difference observed on several materials tested were plotted as shown in Fig. 21.

One of the specimens was then suspended in the furnace by means of a wire, with grips removed, the thermocouples being in the same relative positions, and the temperature observations duplicated. The thermocouple readings with this set-up coincided within the limits of experimental error, which indicates that the difference in temperature between surface and center is due to loss of heat by conduction to adaptors, holders, extensometer arms, etc.

Although the apparent difference in temperature is indicated to be 146° F. (80° C.) as the maximum at 600° F. (315° C.) with the calibration bar used, this apparent difference exceeds appreciably the true difference existing between the surface and the center of the standard $\frac{1}{2}$-in. specimen. The reasons for this are as follows:

When these differences are considered in connection with the temperature differences noted along the surface, the existence of isothermals along the specimen must be assumed, which does not seem warranted.

The rate of heat transfer along a bar which is not at uniform temperature may be represented by the equation:

$$\frac{dH}{dt} = \pi r^2 K \frac{dT}{dl}$$

where $\frac{dH}{dt}$ = rate of heat flow,

πr^2 = area,

K = coefficient of conductivity, and

$\frac{dT}{dl}$ = rate of change of temperature with change in distance from the hotter portion.

From this equation it will be seen that the rate of flow of heat and therefore the temperature difference varies directly with the area.

Reference to the calibration bar will show that the area is twice the area of the standard specimen. Inasmuch as the area is the only varying quantity between the two equations for standard and calibration bars, it is apparent that from this correction alone the temperature difference between surface and center would be reduced very materially below the apparent differences shown. Assuming that there is a temperature gradient between points on the surface of the standard test bar and the center of the section through any of these points, the temperature measured at the surface would approximate more closely the mean effective temperature, which would lie at the point of mean effective area, namely, one-third the distance in from the surface of the bar. For this reason, the temperature as registered by a thermocouple placed against the mid-point of the specimen has been used by the author.

Referring particularly to variations in temperature along the length of the pull section of the standard test bar, observations of the manner in which the bars broke, under load, cast considerable doubt on the possibility of there being any appreciable difference in temperature along the bar.

Considering, therefore, all the experimental and theoretical observations made, we are of the opinion that the effective temperatures, whether they be in the center of the bar or at the ends, do not vary more than 40° F. (22° C.), and from the temperature indicated by the pyrometer, in some cases may be considerably less.

The work of Speller(215), Germer and Woods(209), d'Arcambal(148) and several other investigators, shows that the tendency of present investigation is to use the cylindrical electric furnace, with the thermocouple wire placed against the outside surface of the test specimen.

Before leaving the subject of tension tests of metals at elevated temperatures to discuss special tests of metals at various temperatures, tests of Jeffries and Sykes on wires at both low and high temperatures will be described.

ZAY JEFFRIES(127) AND W. P. SYKES(163)

The investigations of Jeffries and Sykes were mainly in connection with copper, tungsten, Armco iron, nickel and molybdenum wires and the methods of test will be described in detail. In these tests wires were subjected to tension at temperatures from −310° F. (−190° C.) to maximum of 1650 to 1830° F. (900 to 1000° C.). No attempt was made to determine the elastic limit but the other tensile properties, namely, tensile strength, elongation, and reduction of area, were determined at all temperatures.

The apparatus used for these tests is composed of two main parts, the base and the loading mechanism. The base consists of two cast-iron disks, a bottom and a top, that are fastened together by three pieces of steel pipe. The base weighs a little over 100 lb. and is placed on a platform scale. The top of the base portion is provided with a steel tube 0.875 in. in outside and 0.5 in. in inside diameter to which the test pieces are clamped by special clamps. The upper clamp is connected with the loading mechanism. When the load is applied by the handwheel, the test wire pulls on the base and the amount of its pull is measured on the weighing mechanism of the scale. The zero point on the scale is equal to the weight of the base; the scale is kept balanced continually during the test until the wire breaks. The scale reading at the breaking load of the test specimen is then subtracted from the zero reading and the difference gives the breaking load of the specimen.

Liquid Air Tests.—Punch marks 2 in. apart were made on all wires and the clamps were set about 2.5 in. apart, leaving about 0.25 in. between each clamp and the closest punch mark. The test wires were locked in clamps and inserted in the machine and a 1-qt., wide-mouth thermos bottle of the food-jar type, more than three-quarters filled with liquid air, was raised in such a manner that the steel tube containing the test wire was immersed in liquid air. The test wire was completely immersed and hence its temperature was that of boiling liquid air. As soon as violent boiling ceased, the load was applied until the wire broke. The vacuum jar containing the liquid air was then lowered from the steel tube and another vessel containing warm water was substituted for it. When the temperature had been raised by water the clamps were removed.

Tests at 212° F. (100° C.).—These tests were made in boiling water. An electric percolator heater was placed on the platform instead of the vacuum jar and a coffee pot was used for holding the water. The water was kept boiling vigorously till the end of the test.

Tests at 400° F. (200° C.).—These tests were made in hot crisco. Crisco was used because it could be heated to 480° F. (250° C.) with very little volatilization; one of the chief advantages of crisco is that it is very fluid at higher temperatures. The crisco was heated in the same electric heater that was used in the 100° C. tests. The temperature during the test may have varied 3 or 4° C. Several pounds of crisco, however, were used so that the temperature changes were slow. Immediately after each test piece broke, the temperature of the crisco was measured with a mercury thermometer.

Tests above 400° F. (200° C.).—A different scale and different loading mechanism were used and the base of the apparatus modified so that an electric furnace could be used to obtain the proper temperature. A Kron scale with a 30-in. dial graduated in quarter pounds but sensitive to less was used. The electric furnace consisted of an alundum tube 1 in. in inside diameter, and 12 in. long, wound with nichrome ribbon enclosed in a gas-tight steel cylinder. Powdered silica was used as a heat insulating medium between the alundum tube and the cylinder. The cylinder was provided with a connection to a tank of compressed argon, so that a neutral atmosphere could be maintained in the furnace at higher temperatures. The electric furnace was so fastened that the load on the wires was transmitted to the base portion by the lower end of the furnace. The bottom clamp was flanged to fit a seat at the bottom of the furnace housing; the flange was so large that it could not be drawn through the furnace tube. This clamp was fastened to the loading mechanism by means of a clevice.

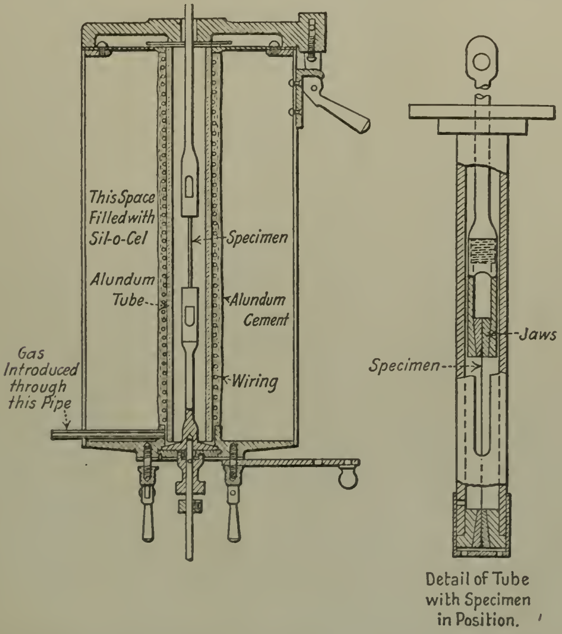


FIG. 22.—Diagram of Furnace Used by Jeffries and Sykes for the Testing of Metals at High Temperatures.

A platinum-platinum rhodium thermocouple was used to measure the temperature. The hot junction was placed in the furnace tube about half way between the two clamps, that is, at about the central point of the test wire. The thermocouple was connected with a Wilson-Maeulen galvanometer with both millivolt and temperature scales. The temperature of the electric furnace could be maintained constant with a wire-wound rheostat.

Details of the furnace and tube with the specimen in position are shown in Fig. 22.

IMPACT TESTS

Guillet and Revillon(60) carried out tests on a Guillery 60-kgm. impact machine. The test pieces were heated in an electric furnace to slightly above the temperature required for the tests, they were then placed on the anvil and temperature noted at time of fracture. The temperature was determined by the use of a thermocouple inserted in a small hole drilled in the specimen and penetrating up to about 3 mm. from the cross-section to be fractured. The ends of the test pieces were covered with asbestos to prevent cooling of the extremities when in contact with the anvil. Tests at as near 212° F. (100° C.) as possible were obtained by using boiling water.

A. C. Langenberg(200, 201) has made impact tests at Watertown Arsenal at the following temperatures: −80, −40, −20, 0, 15, 32, 50, 70, 90, 110, 130, 150, 175, 200, 225, 250, 350, 500, 750 and 1000° F. (−60 to 540° C.), two test specimens being tested at each temperature. Temperatures below the atmospheric were obtained by immersing the test bars in a bath of acetone. The acetone bath was cooled to the desired temperatures down to 0° F. (−18° C.) by means of a calcium-chloride solution cooled by an ordinary ammonia refrigerating apparatus. The lower temperatures were obtained by direct addition to the acetone of carbon dioxide snow. Temperatures from 90 to 350° F. (32 to 175° C.) were obtained by heating the test bars in a Freas constant temperature oven, and from 500 to 1000° F. (260 to 540° C.) the test bars were heated in a Hoskins electric muffle furnace.

The lower temperatures were ascertained by alcohol thermometers, the medium by mercury thermometers, and the higher temperatures by means of platinum-platinum rhodium thermocouples. In tests from −80 to 350° F. (−60 to 175° C.) a thermometer was inserted in a hole drilled in a dummy test specimen and packed with magnesium powder, the dummy and thermometer were placed in the cooling bath or heating furnace in the center of the group of test bars. An additional thermometer indicated the temperature of the heating or cooling medium. When two thermometers gave readings as near alike as it was found possible to obtain, the temperature of each test bar was considered to be very close to the temperature of the dummy test bar as shown by the inserted thermometer. At temperatures from 500 to 1000° F.

(260 to 540° C.) a thermocouple was inserted in the center of the notch of each test bar and the bar was tested when the thermocouple showed that the desired temperature was reached.

FIG. 23.—Charpy Impact Testing Machine Used by Langenberg.

In testing, the heating or cooling apparatus was placed as conveniently near the impact testing machine as possible, and each specimen transferred quickly to the machine, the time in transferring being observed by means of a stop watch. It was found that the temperature of the test bars at the moment of impact closely approximated the desired temperature and it is believed that each specimen was tested at a temperature within 2° F. above or below the temperature recorded.

The large Charpy impact machine used in the tests (Fig. 23) has the following constants:

Weight of pendulum	212.3 lb.
Velocity of impact	25.7 ft. per second
Capacity	2199.5 ft-lb.

The specimen used in these tests was the large notched Charpy impact specimen, 6.102 in. long and 1.181 in. square in cross-section, with the notch 0.591 in. deep by 0.158 in. wide.

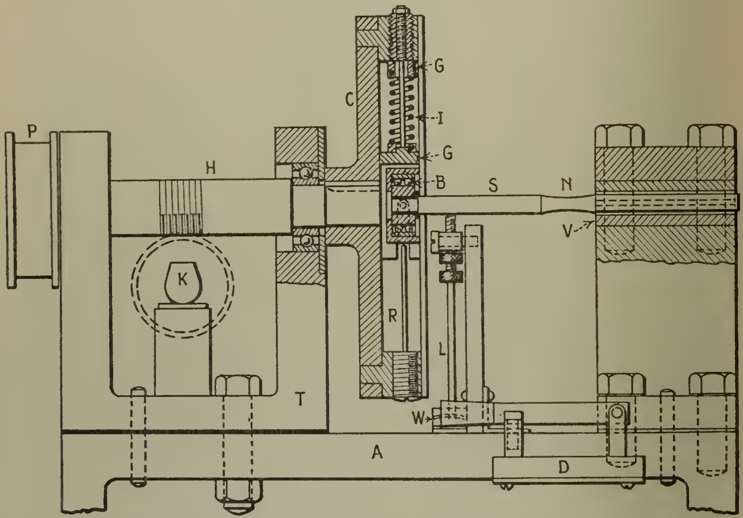


FIG. 24.—Diagram of Rotating-Spring Reversed Bending Testing Machine Used by Moore.

ALTERNATING STRESS TESTS

Not a great amount of research work has been carried out on the effect of various temperatures on the strength of materials under alternating stress. Tests were made by Batson and Hyde(89) at the National Physical Laboratory in England in a machine of the Wohler type, the test piece running at a speed of 2000 alternations per minute in an oil bath heated electrically.

During the past year a considerable number of repeated stress tests of steel at temperatures up to 875° F. (465° C.) have been made in the laboratory of the Investigation of the Fatigue of Metals at the University of Illinois(213) under the direction of Prof. H. F. Moore with the cooperation of the National Research Council, General Electric Co., Illinois Engineering Experiment Station, Engineering Foundation, Western Electric Co., Allis-Chalmers Manufacturing Co., and the Copper and Brass Research Association. The testing machine used in these experiments is shown in Fig. 24 and is a reversed-bending testing machine. In this machine one end of the specimen *S* is held rigid in the vise of *V* and the other end which runs in the bearing *B*, is rotated in a small circle. Sidewise pressure, which can be adjusted by means of a screw, is brought on the bearing *B* by a calibrated indicator spring *I*. The compression of the spring, and hence the load on the specimen, is measured by means of a strain-gage spanning the gage holes *GG* shown near the ends of the spring. The rotating spring is carried in the cross-head *C*. Sidewise motion of the bearing *B* is prevented by placing the bearing in a slot, and excessive displacement of the bearing, when the specimen breaks, is prevented by the rod *R*. The cross-head is driven by a shaft *H*, a pulley *P*, and a motor not shown in the figure. The number of revolutions of the cross-head is measured by the revolution counter *K* which is driven by a worm on the drive-shaft *H*. When a test to destruction is carried out, the fracture of the specimen occurs at the necked-down part *N*, and the broken end of the specimen hits a screw and kicks out a lever *L*. This releases the spring *W*, which then opens the motor switch *D*, thus stopping the motor.

In the elevated temperature investigation a small electric furnace not shown in the figure was added in order to heat the specimen to the required temperature for test. Temperatures were measured by means of a thermocouple in contact with the specimen at its region of maximum stress and temperature was recorded and controlled by a Leeds and Northrup temperature recorder and automatic controller.

Endurance limits (fatigue limits) for completely reversed stress were determined from *S-N* diagrams described in *Bulletins Nos. 124* and *136* of the University of Illinois.

The results obtained by Moore are regarded for the present merely as preliminary. They do, however, give certain interesting indications, and we may expect to find some startling results in tests of this nature as the work progresses.

TORSION TESTS

Bregowsky and Spring made a number of torsional tests on rolled rods at elevated temperatures. In order to insure as nearly comparable results as possible, rods of the same size ($1\frac{1}{8}$ in. in diameter) were purchased in the market and test bars cut off and turned down to uniform diameter of 0.855 in. The length of the turned-down section was 8 in. in nearly all cases.

The same sort of heating apparatus was used as noted under tension tests by Bregowsky and Spring(83). The coil was 12 in. long. Fig. 25 shows the bar and appratus in position. For high temperature, mica plates and asbestos sheets were inserted between the jaws and head of the testing machine to retard the loss of heat.

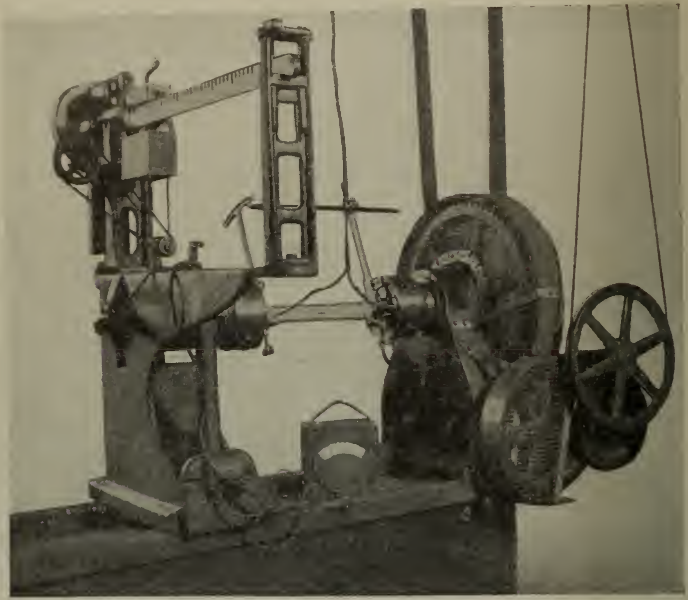


FIG. 25.—Torsional Machine Used by Bregowsky and Spring with Test Specimen and Apparatus in Place.

Elastic limits were determined by plotting readings taken by means of the troptometer, with increments of load, applied very slowly and the corresponding distortion read off the scale. Ultimate strength and elastic limit were given in pounds per square inch and total twist in turns (revolutions of 360 deg. each) with number of degrees in excess.

HARDNESS TESTS

Aitchison(123) gives some results of hardness tests at elevated temperatures on high-speed steels of various compositions. Prof.

C. A. Edwards(120) recently carried out a series of investigations into the hardness of steels at elevated temperatures and in order to readily compare his work with the standard Brinell machine he had to develop an entirely new apparatus.

This hardness testing at elevated temperatures is of great advantage in order to determine the cutting efficiency of tools at various temperatures, and a simple accurate hardness test at elevated temperatures is certainly needed to-day. As this method of test is really in process of development, little can be stated at this time regarding the testing or apparatus.

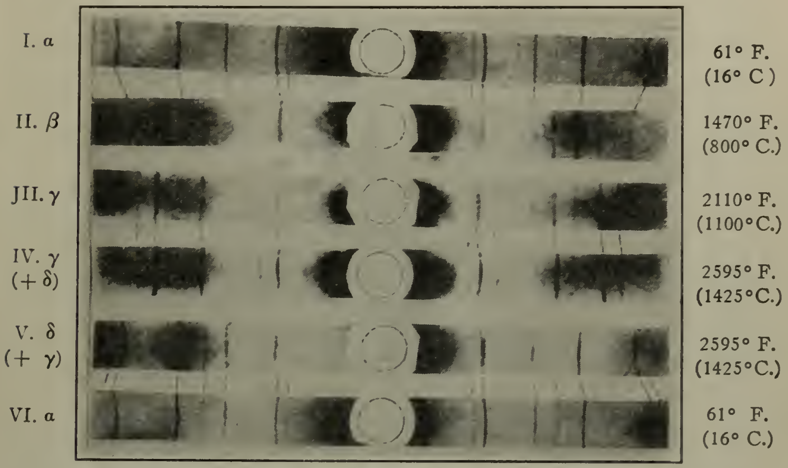


FIG. 26.—Photograms of Pure Iron at Different Temperatures.

X-RAY SPECTROGRAPH

Arne Westgren(165) of Gothenburg has carried out in the Physical Institute of the University of Lund, Sweden, quite an amount of interesting and instructive work with the X-ray spectrograph on iron and steel at elevated temperatures. Lately the X-ray has been used to study the defects in iron and steel castings and it has opened up a field that is both instructive and fascinating. While the X-ray analysis is in its infancy, the writer believes that it will be one of the future methods of testing metals and alloys at various temperatures.

Westgren has shown the importance of the X-ray method of investigation in metallographic research of iron and steel, both at ordinary and elevated temperatures. According to the spectrograms obtained at elevated temperatures it has been shown that a fundamental difference exists between the apparent transformation point A_2 and the critical point A_3. Westgren reported he was unable to find any structural change of iron either above or below the A_2 point. At A_3, however, he finds the atoms of iron are completely rearranged and the iron passes from one crystal class into another. Consequently, the difference between iron of the alpha and beta states is not of the same kind as between the alpha and gamma states. Fig. 26 is a photogram of pure iron at different temperatures.

This investigation has shown that the iron atoms of martensite are oriented in exactly the same way as ferrite, and the difference in hardness between these two structural constituents is not due to the iron but to the carbon present in the martensite. This has an important bearing on the testing of metals at elevated temperatures, for by the use of the X-ray spectrograph, problems now solved only by empirical methods may be open to theoretical treatment and become based on rational scientific knowledge.

It is the belief of such investigators as Rosenhain, Jeffries and Lester that the real future advancement of a knowledge of the internal structural changes in metals at various temperatures lies in the direction of the X-ray spectrum. It is to be hoped that investigators will actively take up this very interesting method of research, as it gives great promise of revealing, in a simple manner, the more complicated problems of structural changes in metals at various temperatures.

LONG-TIME TESTS

In the foregoing series of tests the time consumed in most cases has been so short as to give little idea as to the probable behavior of the metals or alloys when maintained for considerable periods under the applied conditions of stress and temperature. Recent experimental work by J. H. S. Dickenson(173), calls attention to the influence of the time factor in determining the temperature up to which certain steels can support a given load and, by inference, the load which can be borne at any given temperature.

Two series of tests were run by Dickenson, one to determine duration at constant load and constant temperature, and the other at constant load and uniform rate of temperature increase. In both series of tests a load of 19,000 lb. per sq. in. on the specimen was used and the temperature varied from 932 to 1769° F. (500 to 965° C.). The tests were carried out on six samples of steel made into bars of 8-in. gage length and 0.40 in. in diameter.

The tests were carried out with one exception on heat-treated steel, the exception being a cast chrome-nickel steel. The apparatus used was arranged for six tension tests simultaneously, with electric furnaces wired in parallel, the temperature being recorded by a Cambridge thread recorder, the couples being checked before and after use. The testing machines were of special construction and designed for this investigation.

Duration Tests at Constant Load and Constant Temperature.—In conducting these tests, care was taken in applying the load so that no live load was momentarily produced and the temperature was steadily increased to the desired point where it was maintained day and night until fracture occurred or until it was deemed unnecessary to continue. A daily measurement was made of the change in distance between the gage points on the specimen, this measurement being readily obtained because the gage marks were outside the furnace. More frequent observations were made when rapid extension of the specimen required it or when rupture became imminent at the end of long runs.

A series of test pieces for each class of steel was run at 90° F. (50° C.) ranges, such as 1022 to 1112° F. (550 to 600° C.), 1112 to 1202° F. (600 to 650° C.), and so on.

Tests at Constant Load and Uniform Rate of Temperature Change.—In these tests, after the test piece had been placed in position in the furnace and the load applied, the gage length was measured. The temperature was slowly raised by means of a specially constructed rheostat at the uniform rate of 180° F. (100° C.) per hour, an over-all measurement being made at 212° F. (100° C.) and thereafter on reaching each additional 90° F. (50° C.), care being taken to make this coincide with half-hourly periods. Later as the rate of extension increased, more frequent measurements were made, usually in six-minute periods and finally the temperature at which the test specimen fractured was carefully noted.

Tables were worked out and graphs made, showing estimates of the probable lives of test specimens subjected to constant load and temperature for long periods, and eventually withdrawn but not broken. An estimate of the probable time before rupture would have occurred, had the test proceeded, was obtained in each case by comparing the time required to produce the same extension in unbroken and broken specimens of the same steel. The estimates given, however, are only of general interest.

In 1922 the author(188, 189) carried out a series of tests for 400 hours on cast steel at constant load and constant temperature. The standard A.S.T.M. test bars were used, of 2-in. gage length, 0.505 in. in diameter and the apparatus used was the same as described in the tension tests. The temperature of the specimen was raised at a uniform rate until a maximum of 1100° F. (600° C.) was reached, and a load of 21,000 lb. per sq. in. placed on the specimen. This temperature and load were maintained night and day for 400 hours, after which the load was removed and the temperature allowed to drop to normal. The original gage length was remeasured for any permanent extension or deformation.

The U. S. Bureau of Standards is now working on apparatus for testing metals at constant temperature over long-time periods, but as yet little work has been accomplished.

A knowledge of the behavior of metals at elevated temperature over long periods would undoubtedly be of great technical importance for the reason that these tests tend to cast grave doubts on our ideas as to the yield point or elastic limit of certain metals in common use and it would appear that we may be compelled to revise our ideas along these lines. Since it is now generally agreed that design should be based on the yield point or elastic limit, the matter becomes important.

METALLIC OXIDATION AT ELEVATED TEMPERATURES

One neglected type of study in the testing of metals at elevated temperatures is the metallic oxidation of the metals or alloys when exposed to temperatures considerably higher than the atmospheric range, and more especially the attack of atmospheric oxygen upon the exposed metallic surfaces. That the problem is a difficult one to contend with is connoted by the practical dominance of a certain alloy in electric heating. Proprietary interest may account in part for the paucity of information available in technical literature upon even the most general facts on the behavior of metals and alloys when exposed to elevated temperatures. A very interesting and instructive paper on this subject was published by Pilling and Bedworth(191) in March, 1922.

Dickenson(173) published results of scaling tests on metals at elevated temperatures. In his experimental work eight typical steels were selected for examination. From each sample nine cylinders each 0.50 in. in diameter by 2 in. in length were machined, polished with emery and weighed. Each of these cylinders was heated for a total time of 100 hours. In order to maintain throughout the 100 hours a practically uniform rate of oxidation, which slows down as the adhering scale increases in thickness, the heating was carried out in 18 periods of approximately $5\frac{1}{2}$ hours each, the specimens being scraped free from scale and weighed after each cooling. Two types of furnace were used for heating the specimens. An electric furnace surrounded by air was used for the lower temperatures, while for the higher ranges the less pure atmosphere of a gas furnace was employed.

In a table by Dickenson the scaling rate in ounces per square inch per hour at mean temperatures indicated is given, including the results from both electric and gas furnaces. It appears that the rate of scaling at 1600° F. (870° C.) is much the same in the two types of furnace, at any rate, when the gas muffle front is slightly open and burners are receiving full air as in the present case so that the lower series and the upper series may be considered satisfactorily linked.

A series of tests was carried out by the writer(188, 189) in 1922 on the rate of scaling of cast steel. In the experimental work 1-in. cubes were used, each cube being carefully ground on an emery wheel to remove any foreign substance adhering to it, after which they were carefully calipered and weighed. They were then subjected to 100 hours treatment in an electric furnace in which was maintained ordinary atmospheric conditions. In order to maintain a uniform rate of oxidation, the specimens were removed approximately every six hours and scraped free of adhering scale and weighed. A graphical chart was plotted showing the amount of scale in ounces at the temperatures noted. It was found from these tests that little or no scaling existed when steel was exposed to temperatures below 1100° F. (600° C.) and that the formation of scale started at about that temperature and increased rapidly, while at 1700° F. (925° C.) the amount of scaling may be considered excessive.

CONCLUSION

The writer has endeavored to describe in outline the latest methods of testing metals at various temperatures. It will be noted that the furnaces and other apparatus, procedure, etc., used by the various investigators differ to some extent and are by no means standardized, each investigator believing his method to be the correct one. Very little definite information on the rational mechanical testing of metals at elevated temperatures has been obtained.

The effect upon the physical properties of metals of raising the temperature cannot as yet be stated in terms of a definite law. It may be generally stated that the tensile strength and elastic limit of steel decrease and the elongation and reduction of area increase as the temperature is raised. Of course there are exceptions to this rule. It has been noted in nearly all the investigations that at certain temperatures between 500 and 800° F. (260 and 425° C.) the tensile strength rises and the elongation and reduction of area decrease, but the elastic limit continues to decline steadily. Therefore, to use the tensile strength as a basis of design would be far from correct. This condition of marked rise in the tensile strength and fall in the elongation and reduction of area is known as "blue brittleness" from the original German term "Krupp-Krankheit" and is to some extent the limit of our general knowledge. Rosenhain and Archbutt(130) found a formation of intercrystallin cracks, which eventually produced failure in boiler plate. These plates were used at elevated temperatures and it is thought that the long sustained load at these temperatures caused the amorphous cement at the grain boundaries to flow and eventually break without deformation of the grains. Jeffries(184) has made quite a study of the physical changes in iron and steel at various temperatures and the conclusions reached are both interesting and instructive. Langenberg(186) believes that "blue brittleness" is a distinctive property of free ferrite, and furthermore that "blue brittleness" is not the property of free ferrite at blue heat, but rather is a property resulting from a mechanical deformation of free ferrite at blue heat or lower temperatures. We believe that this is a subject that should be given careful consideration in the testing of metals at elevated temperatures.

Again, we find that results obtained in actual practice have not always been in accordance with those obtained experimentally. One instance with which the writer is acquainted is a set of valves operating at 950° F. (510° C.) for several years which are still giving excellent service, yet most of our experimental work in testing metals at elevated temperature shows that steel is very weak at this temperature.

The explanation of such inconsistencies is probably to be found in the fact that the alterations in the physical properties of metals and alloys due to variations of temperature are not always of the same nature. With any increase in temperature and consequent molecular activity we may expect a gradual falling off in tensile strength until at the melting point of the metal the tenacity becomes nothing. Allotropic changes in metals are accompanied by changes in physical properties. For instance, iron undergoes certain changes at certain temperatures. Zinc is brittle at ordinary temperatures but when heated to certain temperatures it becomes malleable and again loses this property at higher temperatures. Tin at low temperature undergoes a molecular change and falls to powder. Such changes are abnormal, and, except in the case of iron, very little is known as to what takes place when metals are alloyed and subjected to various temperatures.

Some metals and alloys undergo a gradual change in their crystallin character, which is greater at elevated or low temperatures. This change may be simply an increase in size of crystals or may be a change in crystallin structure. For instance, tests show that brass or bronze when heated to temperatures beyond 400° F. (205° C.) becomes very treacherous, the tensile strength and elongation both decreasing as the temperature is raised, and the crystal size becoming very coarse. Alloys containing two or more constituents are more likely to suffer failure at elevated temperatures than those containing only one constituent, especially if one of the constituents is a eutectic. The eutectic often has a melting point lower than the constituent metals and therefore its strength is affected at a lower temperature; and if the eutectic forms a network or cement around the grains or crystals, its strength represents the strength of the alloy.

In these several causes of failure, the gradual change of structure occurs only after a lapse of time, and this is one reason for failure of metals or alloys that have shown good results when tested in a short time at elevated temperatures. Tests carried out on an alloy at short duration are not always sufficient to indicate the behavior of a metal in service.

Another example which may be cited is the large columnar structure often found at certain temperatures in nickel-copper alloys.

Very little appears to be known about the changes that take place in metals or alloys when subjected to high-temperature service, and it seems advisable that a complete structural study with the aid of a microscope should be made of metals when tested at various temperatures. The microscope together with the X-ray will, we believe, be found valuable in future tests.

In summing up, we would say that in carrying out research into methods of testing metals at various temperatures, it should be our aim to carry out such tests as will approximate the trying conditions of service. This fact is often lost sight of in making an investigation. To be of any value the investigation should have a definite aim and be carefully planned. A general survey of the entire field should be made, as one method of test may be of value to a single consumer or producer, but of little or no value to others.

The author hopes that we will soon be able to standardize our methods of test in this field of great importance, in which, it may not be amiss to mention, continental Europe has made rapid progress.

AVAILABLE DATA ON THE PROPERTIES OF IRONS AND STEELS AT VARIOUS TEMPERATURES[1]

By H. J. French[2] and W. A. Tucker[3]

Introduction

Despite the fact that attention has been called repeatedly during the past few years to the incomplete and unsatisfactory nature of available information on the properties of ferrous metals at high and low temperatures, a vast amount of test work has been carried out by many investigators. Not all of the results have been published but much of the information is now in print and there can be developed many interesting and important comparisons in addition to the special features emphasized in each report. However, it is not intended to present a complete résumé of all this material but rather to give a brief sketch of the character of published information. Detailed study of any of the phases covered in the literature may be made by consulting the references in the Bibliography which will be found appended to this paper.

No attempt will be made to reproduce or discuss results for all the ferrous alloys which have been tested nor can the tests made by all investigators of a given alloy be mentioned. However, there will be given representative graphs or other forms of data to show the general effects of temperature variations upon the properties of irons and steels, particularly with respect to those features of interest to engineers. Reference will also be made to some of the "heat-resisting" alloys now in use or proposed for high-temperature service.

Mechanical Tests at Various Temperatures

IMPORTANCE OF THE TIME FACTOR AT HIGH TEMPERATURES

Before summarizing some of the principal features shown by the available data, attention should be called to the importance of the time factor in mechanical tests of metals at high temperatures. Howard(17)[4] reported that the "rate of speed of testing which might modify the results somewhat with ductile material at atmospheric

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[1] Published by permission of the Director of the U. S. Bureau of Standards.

[2] Physicist (Metallurgy), U. S. Bureau of Standards, Washington, D. C.

[3] Laboratory Assistant, U. S. Bureau of Standards, Washington, D. C.

[4] The boldface numbers in parentheses refer to the papers of the Bibliography appended hereto, page 124.

temperature had a very decided influence upon the apparent tenacity at high temperature." Steel containing 0.81 per cent of carbon was tested at a slow speed which produced rupture in from 5 to 10 minutes and also under rapidly applied stresses (in which case the time was from 2 to 8 seconds). Nearly the same strength was displayed whether slowly or rapidly fractured at temperatures below about 600° F. (315° C.), this being a comparatively brittle metal at moderate temperatures. Above this temperature the apparent strength of the rapidly fractured specimens largely exceeded the strength of the others. The higher the temperature the wider apart were the results. An extreme illustration of this kind was furnished by a specimen tested at 1410° F. (765° C.) which when ruptured in 2 seconds showed a tensile strength of about 62,000 lb. per sq. in., whereas at ordinary speed of testing a corresponding bar fractured at 33,240 lb. per sq. in.

TABLE I.—EFFECT OF SLOW LOADING ON THE TENSILE PROPERTIES OF FIREBOX BOILER PLATE AT DIFFERENT TEMPERATURES [FRENCH (179)].[1]

C, 0.19; Mn, 0.43; P, 0.020; S, 0.031

Temperature of Test		Rate of Loading	Proportional Limit, lb per sq. in.	Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Remarks
deg. Fahr.	deg. Cent.						
315	155	Adopted standard[2]	26,600	58,100	24.9	49.3	Average of 3 tests.
315	155	$6\frac{2}{3}$ hours from 22,000 to 47,000 lb. per sq. in.[1]	......	64,300	22.8	45.9	Average of 2 tests.
565	295	Adopted standard[2]	14,300	66,400	25.9	53.1	Average of 3 tests.
565	295	$3\frac{1}{2}$ hours from 9,000 to 20,000 lb. per sq. in.	......	60,000	36.0	59.2	
865	465	Adopted standard[2]	13,200	47,500	33.6	68.5	Average of 3 tests.
865	465	6 hours from 9,000 to 30,000 lb. per sq. in.	......	33,600	42.0	78.4	

[1] Note the apparently anomalous behavior with respect to rate of stress application at 315° F. (155°C.) as compared with higher temperatures.

[2] Adopted standard averages about 0.05 in. per minute extension.

Similar effects are observed in comparison of extremely slow and ordinary rates of loading as shown in Table I, which is taken from tests by one of the authors(179).

Hopkinson and Rogers(55) reported that as the temperature rose the stress-strain relations in steel underwent remarkable changes which might best be expressed by saying that the variously called "creeping," or "*elastiche nachwirkung*," or "time-effect," increased greatly with temperature. While such effects might be detected at ordinary temperatures they attained a different order of magnitude at red heat, 1100° F. (600° C.). The effect of "creeping" was found to make the determination of Young's modulus a matter of some uncertainty for the extension of a bar stressed at 1110° F. (600° C.)

varied 15 per cent or more depending on the time of application of load. For very short applications of the order of one or two seconds, the strain produced approached a definite limiting value which, if used in determination of the modulus, made it independent of the manner of loading and a physical constant.

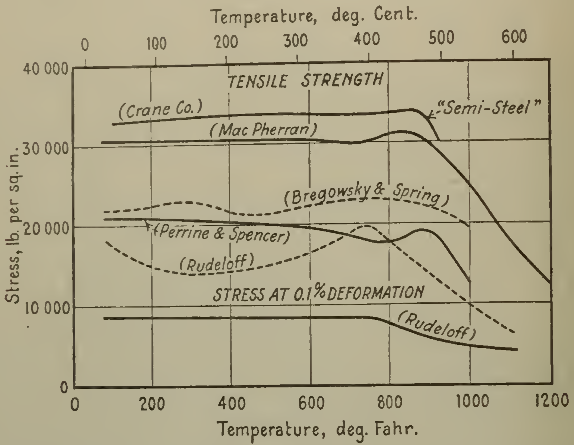

FIG 1.—High-Temperature Tensile Properties of Cast Irons and Semi-Steel as Reported by Various Investigators.

Investigator	Bibliography Reference No.	Chemical Composition, per cent							Remarks
		Combined Carbon	Graphitic Carbon	Total Carbon	Mn.	Si	P	S	
MacPherran...	(128)	....	....	....	0.64	1.84	0.52	0.11	Annealed at 1100° F. (595° C.) before test.
Bregowsky and Spring.......	(63)	0.17	3.31	....	0.60	2.57	0.73	0.10	
Perrine and Spencer.....	(75)	....	....	2.69	....	....	....	....	Curve based on very few tests.
Rudeloff[a]......	(25)	....	....	3.56	0.93	2.64	0.52	0.05	Curves are averages from both wet and dry sand castings.
Crane Co......	(148)	"Semi-steel" or "ferro-steel"				......	......	......	In reality a low-carbon cast iron with high Mn and low Si.

[a] 1000 lb. per sq. in. = 0.7031 kg. per sq. mm.

Many other tests including those of Robin(71) and more recently Chevenard(124) and Dickenson(172) throw light upon the time effect and its importance in any discussion of the high-temperature properties of metals.

Under the conditions outlined it should therefore be recognized that terms such as "proportional limit," "yield point," "tensile strength," etc., which are used in this report, represent values obtained in each case under given conditions of test and do not necessarily have the same significance throughout a large part of the temperature range considered as in tests at room temperatures.

TENSION TESTS

Cast Irons, Semi-Steel and Malleable Iron.—The results of tension tests reported by a number of investigators for cast irons, semi-steel and malleable iron are shown graphically in Figs. 1 and 2. The discrepancies in numerical values for the various irons, which are not in all cases completely identified, is relatively unimportant for the moment. The principal feature to be observed for the three types of product is the small change in tensile properties with temperature rise from 70 to about 800° F. (20 to 425° C.). There are some indications of a maximum in the tensile strength – temperature curves at about 600 to 800° F. (315 to 425° C.), but this is smaller than in the case of carbon steels and for most practical purposes the tensile values may be considered nearly constant throughout the specified range. With further increase in temperature there begins a "softening" which becomes quite rapid above about 900° F. (480° C.).

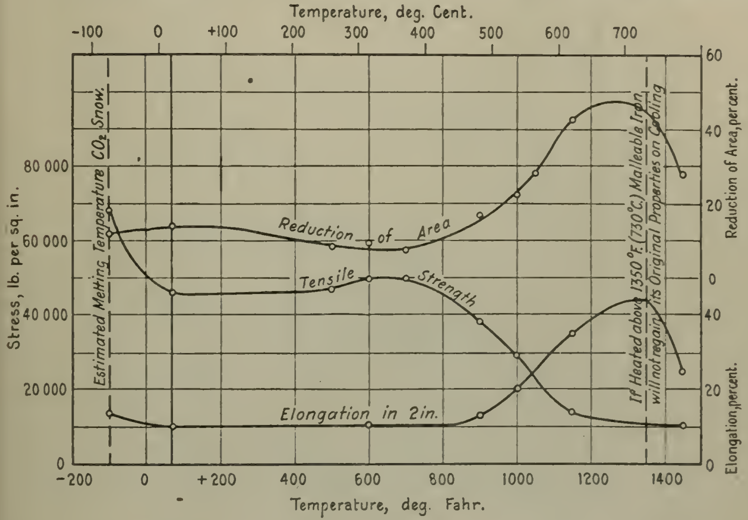

FIG. 2.—Tensile Properties of Malleable Cast Iron at Various Temperatures [Schwartz (131)].

Tests made on specimens 0.634 in. in diameter, ground to size before annealing. The results are known, according to Schwartz, to be unaffected by shrinkage or other defects.

Decrease below 70° F. (20° C.) results in a "stiffening" of the metal as shown by increased tensile strength and some decrease in elongation and reduction of area in the case of malleable iron. In general the effect is accompanied by increased brittleness.

Wrought Iron and Mechanically Worked Steels.—By far the largest number of tests in tension have been made on mechanically worked steels with or without subsequent thermal treatments. Many interesting comparisons are possible but it is impracticable to include in this report more than a brief summary of features having very general interest and to reproduce data for more than a few steel types.

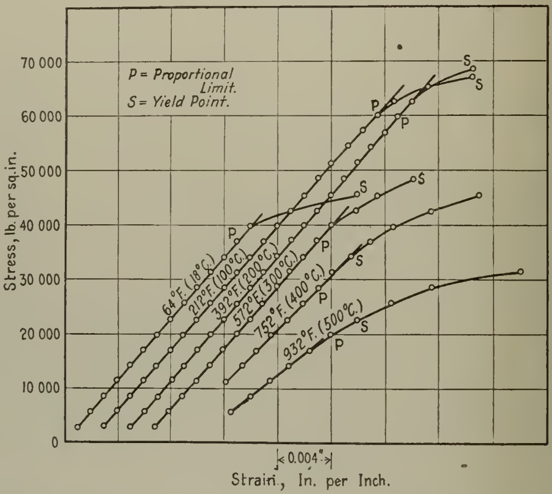

FIG. 3.—Effect of Temperature on the Stress-Strain Relations in Tension of 0.37-per-cent Carbon Steel [Welter (164)].

NOTE.—1000 lb. per sq. in. = 0.7031 kg. per sq. mm.

Figs. 3 to 8, inclusive, show the effect of temperature variations upon the proportional limit, tensile strength, elongation, reduction of area, and the stress-strain relations, including the modulus of elasticity, of carbon and some alloy steels.[1] While an attempt has been made to choose representative results for these graphs it should be kept in mind that they are based on tests of individual heats under specific test conditions. Variations in numerical values may be

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[1] Graphs are not given for wrought iron as the changes in properties are quite similar to those shown for low-carbon steels.

expected when comparing tests of additional heats of the same type in one laboratory or of the same heat in different laboratories.

Some of the important facts, which may be deduced from available results of a large number of similar tests, may be summarized as follows:

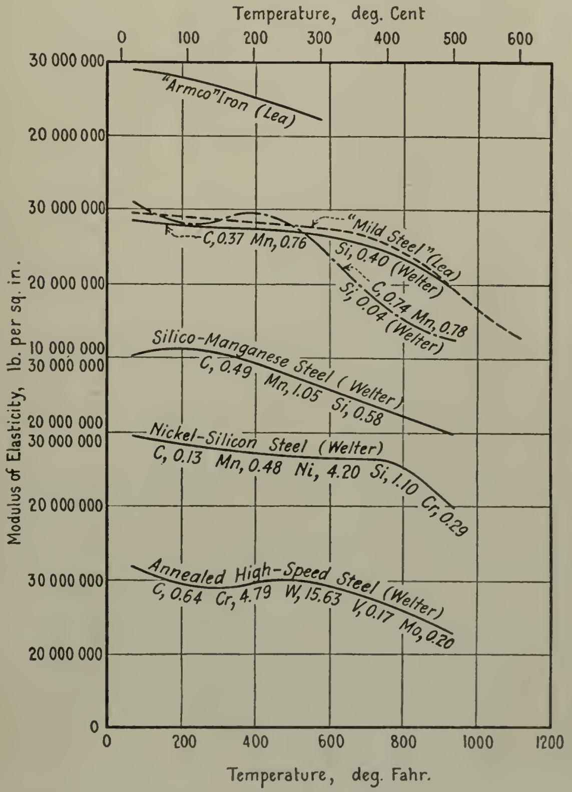

FIG. 4.—Effect of Temperature on the Elastic Modulus of Various Steels in Tension. The work of Welter is given in item (164) of the bibliography; that of Lea in items (103) and (187).

1. The effect of temperature rise to about 1100° F. (600° C.) is to reduce tensile strength, proportional limit and the elastic modulus and greatly increase ductility and the tendency to creep in wrought iron and steels. Certain combinations of composition and treatment, notably normalized chromium-

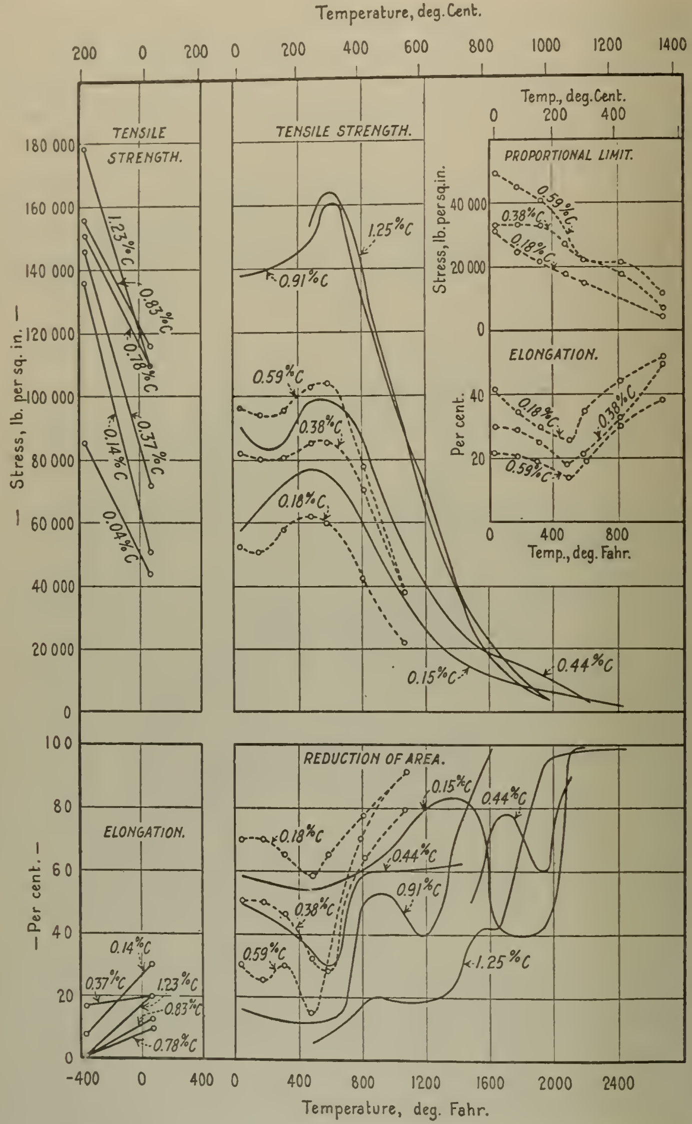

FIG. 5.—Effect of Temperature on the Tensile Properties of Carbon Steels as Determined by Various Investigators.

Solid lines at elevated temperatures are results reported by Dupuy (150) for normalized steels; dotted lines are results on normalized steels obtained by the authors (196). Results below room temperature are those reported by Hadfield (54) for annealed steels containing about 0.1 to 0.3 per cent of manganese.

vanadium, quenched-and-tempered stainless and air-cooled 28-per-cent nickel steels are strongest at ordinary temperatures,

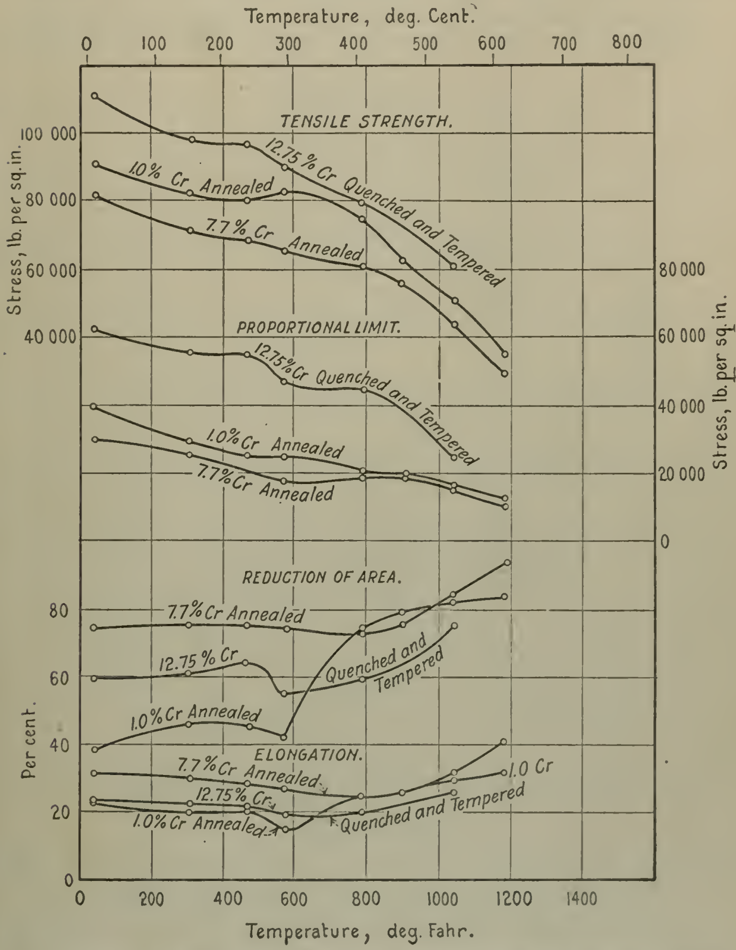

FIG. 6.—Effect of Temperature on the Tensile Properties of Various Chromium Steels Containing 0.3 to 0.4 per cent of Carbon. (Tests by the Authors.)

Annealed = Annealed by heating for 45 min. at 1650° F. (900° C.) and furnace cooling.

Quenched-and-Tempered = Oil quenched from 1750° F. (955° C.); then tempered 45 min. at 1250° F. (675° C.) and air cooled.

but carbon and the majority of alloy steels show maximum tensile strength values and minimum ductility in the range of 400 to 650° F. (205 to 350° C.).

2. The proportional limit of medium or low-carbon steel, which has been largely relieved of stress by suitable treatment decreases with rise in temperature. In highly stressed metal, resulting from cold or blue-work or quenching and that having

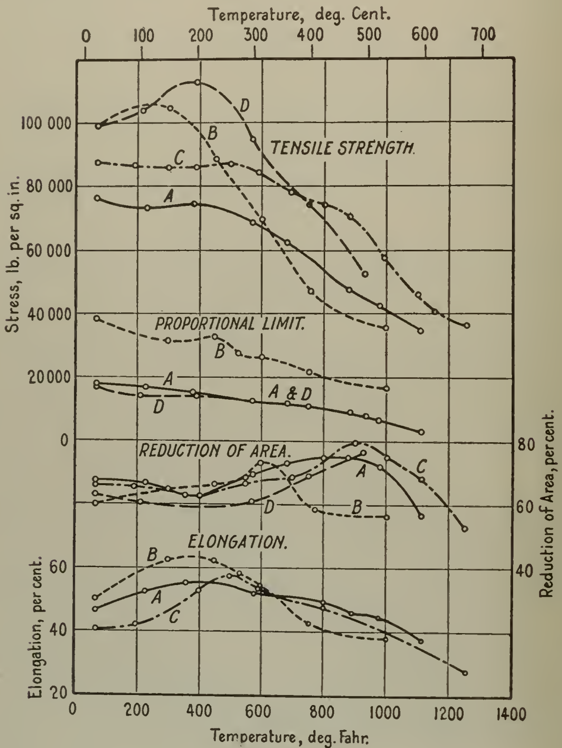

FIG. 7.—Effect of Temperature on the Tensile Properties of Steels Containing from 25 to 35 per cent Nickel as Determined by Various Investigators.

A = 38-per-cent nickel steel reported by French (196); first air cooled from 1475° F. (800° C.).

B = 1-per-cent nickel steel reported by Bregowsky and Spring (83); tested in condition "as received."

C = 34-per-cent nickel steel reported by MacPherran (158); tested as forged.

D = 5-per-cent nickel steel reported by Welter (164).

residual stress, such as often exists in thin sections of hot-finished steel, the proportional limit either remains at approximately its room-temperature value over a well-defined interval or shows an increase with first rise in temperature.

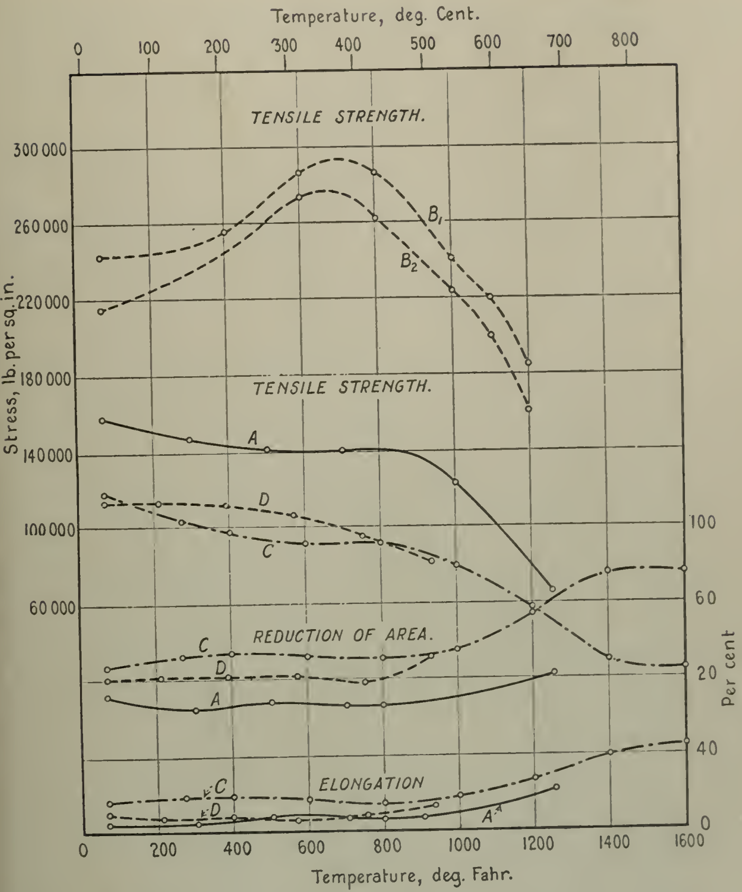

Fig. 8.—High-Temperature Tensile Properties of Annealed or Quenched-and-Tempered High-Speed Steels Reported by Various Investigators.

	Investigator and Reference	Type Composition, per cent				Preliminary Treatment
		C	Cr	W	V	
A	MacPherran (158)	0.68	3.36	19.3	0.88	2300° F. (1260° C.) oil; tempered 1400° F. (760° C.)
B_1	d'Arcambal (148)	0.65	3.62	17.8	0.95	2350° F. (1290° C.) oil; tempered 1100° F. (595° C.)
B_2	d'Arcambal (148)	0.69	3.13	13.9	1.68	2350° F. (1290° C.) oil; tempered 1100° F. (595° C.)
C	Spooner (162)	0.66	3.15	15.9	0.70	Annealed at 1660° F. (905° C.)
D	Welter (164)	0.64	4.79	15.6	0.17	"Annealed"

3. From the standpoint of high strength and limit of proportionality of steels at elevated temperatures, the temperature scale may be divided roughly into three parts: (1) the range 70 to about 850° F. (20 to 450° C.); (2) the range 850 to 1100° F. (450 to 600° C.); (3) above about 1100° F. (600° C.).

4. In the lowest range, high strength and proportional limit are functions of composition and heat treatment and in general combinations giving highest strength at ordinary temperatures show similar superiority throughout the entire range. It is, however, advisable to keep the carbon low since decreased ductility becomes more marked with increase in carbon content, particularly in the blue-heat range.

5. The upper limit in the second or "transition" range requires nearly full tempering following hardening for stability, so that in most cases the benefits to be derived from heat treatment are limited (except in the lower portion of the range) and high strength and limit of proportionality are more largely functions of composition. While short-time tests reported do not give quantitative comparisons for steels subjected to sustained loads, on account of the importance of the time factor, it would be reasonably expected that steels having highest limits of proportionality would be able to sustain higher loads than those with low proportional limits though not necessarily in direct proportion to observed values. On this basis of comparison it appears possible to improve the properties of steel by adding such elements as chromium, cobalt, uranium, molybdenum and vanadium.

6. The drop in strength and proportional limit of steels at temperatures around 1025° F. (550° C.) is permanent for most practical purposes, so that it would appear improbable that commercial steels can be produced to withstand continuously, fairly large loads at temperatures above about 1200° F. (650° C.) except when large proportions of one or more alloying elements are added to reduce the iron content to such a low value that the resulting product cannot correctly be called steel, or in special cases where extremely large proportions of special compounds are present.

Cast Steels.—In general, the effect of temperature increase on the mechanical properties of cast steels is similar to that on mechanically worked steels. However, the actual values obtained in tests will differ materially up to about 800 to 1000° F. (425 to 540° C.) and to a somewhat less extent at higher temperatures from those values observed in similar steels after mechanical work. As both chemical and physical characteristics play a predominant part at slightly

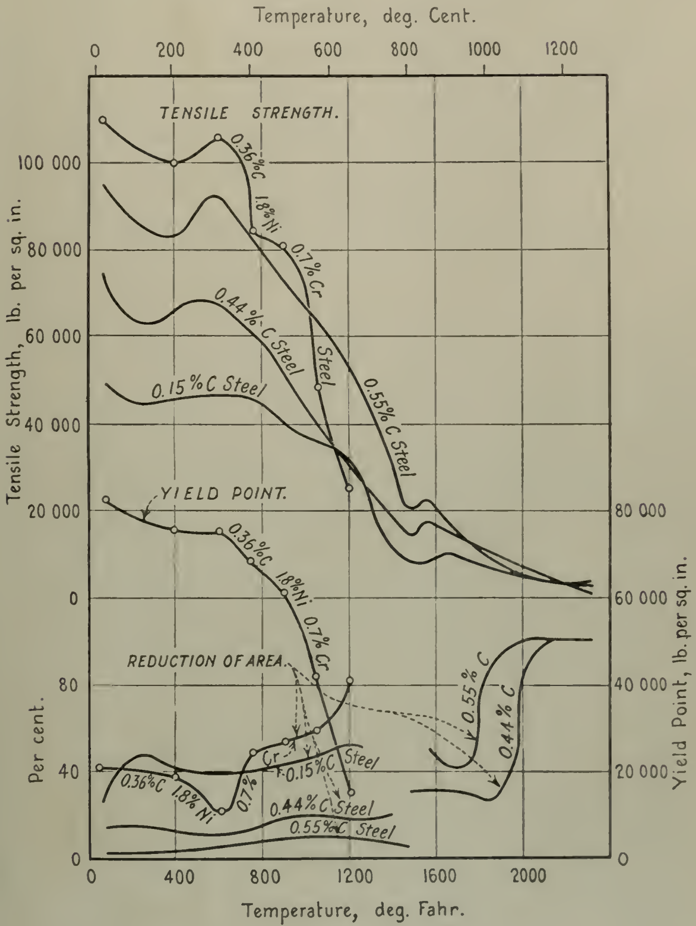

FIG. 9.—Effect of Temperature on the Tensile Properties of Cast Steels (Various Investigators).

Results on carbon steels are those reported by Dupuy (150); those for the nickel-chromium steel were obtained from V. T. Malcolm, Chapman Valve Manufacturing Co.

elevated temperatures in the latter class of steels, so will these same factors, as reflected in the details of casting practice and heat treat-

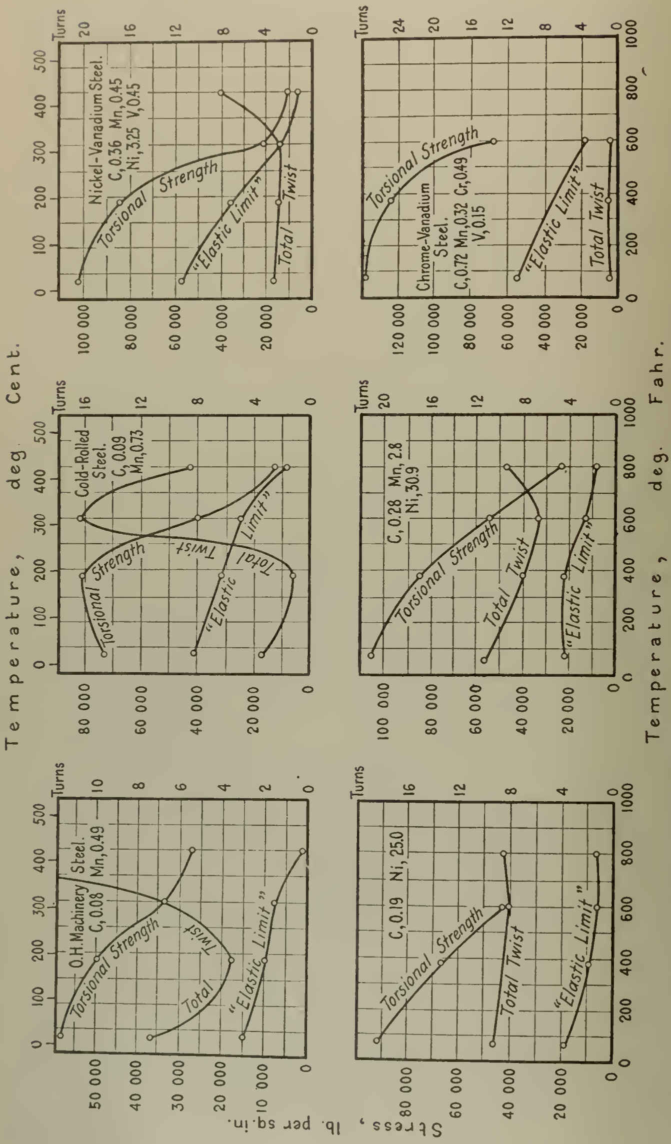

FIG. 10.—Effect of Temperature on the Torsional Properties of Various Steels [Bregowsky and Spring (83)].

"Elastic limits" determined from stress-strain relations obtained with a troptometer. Specimens had 8-in. gage length and were 0.855-in. in diameter, except the 30-per-cent nickel steel which was 1 in. in diameter. All tests made on material as received.

ment, be of prime importance in determining the properties observed in cast metals. They are, of course, to be considered of importance at all temperatures but the weakening effect on all alloys containing large proportions of iron becomes so marked when the temperature becomes high that it obscures, at least in large part, the differences referred to. Representative results obtained on cast carbon and nickel-chromium steels are shown graphically in Fig. 9 and in view of the previous discussions no further comments will be added.

TORSION TESTS

Very little has been published concerning the torsional properties of ferrous metals at various temperatures. The report of Bregowsky and Spring(83) is the only one that has so far come to the authors' attention giving results in the range 70 to 800° F. (20 to 425° C.) and some of the results are reproduced in Fig. 10. While insufficient data are given from which to draw general conclusions, a marked "softening" is observed in all steels tested when the temperature is raised from that of the room to 800° F. (425° C.). However, there appears to be a range of minimum ductility in the neighborhood of 400 to 600° F. (205 to 315° C.) as shown by the small number of turns (twists) before failure. This coincides quite closely with minimum values of elongation and reduction of area observed in tension tests of similar materials.

While considering the torsional properties of ferrous metals attention should be drawn to the qualitative experiments described by Brearley[1] to show the effects upon steels of temperatures in the neighborhood of those used in hot working. A bar of steel, either rectangular or appropriately marked so that the twisting could readily be followed, was heated to about 1800 to 2000° F. (1000 to 1100° C.) at one end and then removed from the furnace to allow the heat to taper down until, within 3 or 4 in. from the colder end, it was at perhaps 1100° F. (600° C.). The hot end was then placed in a vise and the bar twisted from the colder end. In nearly all cases there was a twist of short pitch at the hottest end; then somewhere down the metal at intermediate temperatures came a twist of longer pitch and finally there was a twist of shortest pitch where the metal was coldest.

Very recently similar experiments were carried out more carefully by Sauveur(150) who found that such discontinuities in the twist were associated with an independent A_3 transformation; hence they were observed in iron or steels containing less than about 0.40 per cent carbon. This temperature range within which a "critical twist"

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[1] Discussion of report by Dickenson (172).

was observed may be called a zone of "reduced malleability" and coincides with the so-called "hot-short" range long recognized by mill men for the very pure iron known as Armco or ingot iron. Discontinuities in mechanical properties – temperature curves in this range have also been shown in tension tests by Rosenhain(69) and others.

HARDNESS TESTS

Hardness tests, using the Brinell method, have been reported by Brinell(53), Kürth(62), Robin(63) and Ito(198), etc. As shown in Fig. 11,

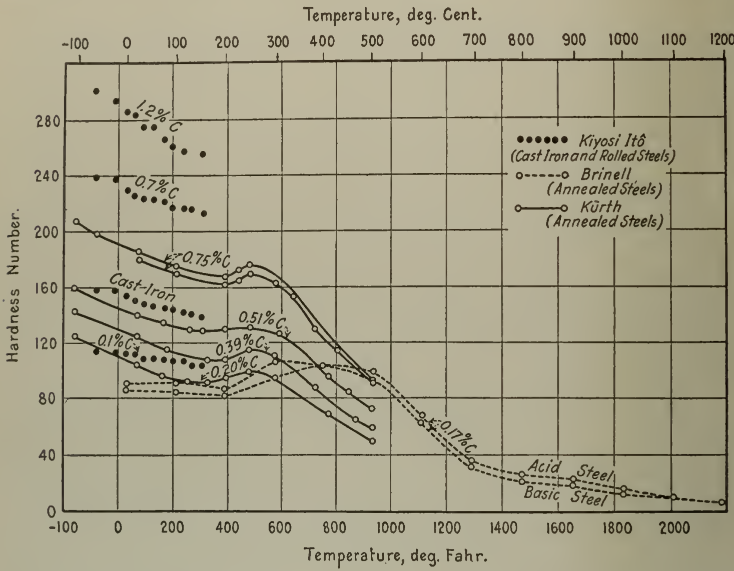

FIG. 11.—Brinell Hardness of Cast Iron and Carbon Steels at Various Temperatures (Various Investigators).

Refer to bibliography, items (53) (Brinell), (62) (Kürth) and (198) (Ito).

the hardness decreases progressively with temperature rise from −80 to 2200° F. (−60 to 1200° C.) with the exception of a fairly narrow temperature range around "blue heat" where a rise in temperature results in an increase in hardness. This effect is observed between 400 and 600° F. (205 and 315° C.) in the hardness-temperature curves of Kürth for carbon steels and coincides with the zone of minimum ductility or maximum strength shown in most tension and torsion tests of similar alloys; in the case of Brinell's curves it extends over a wider range and occurs at somewhat higher temperatures.

CRUSHING TESTS

What may be called the "deformational characteristics" of irons and steels have been very carefully studied throughout a wide temperature range by Robin(71). The extent of his investigations prevents a complete summary but there are a number of features relating particularly to crushing tests and comparisons of crushing resistance with other mechanical properties which should be referred to in some detail. Among these are the following:

"The work necessary to effect a given crushing varies according to the number of blows of a given intensity which produced this crushing. The curves of crushing or of the resistance to crushing, in terms of the number of blows, are hyperbolic and depend on the hardness and on the elasticity of the metal. The direction of the curves changes when the heat diminishes the resistance of the metal, whereupon the latter behaves like a soft metal."

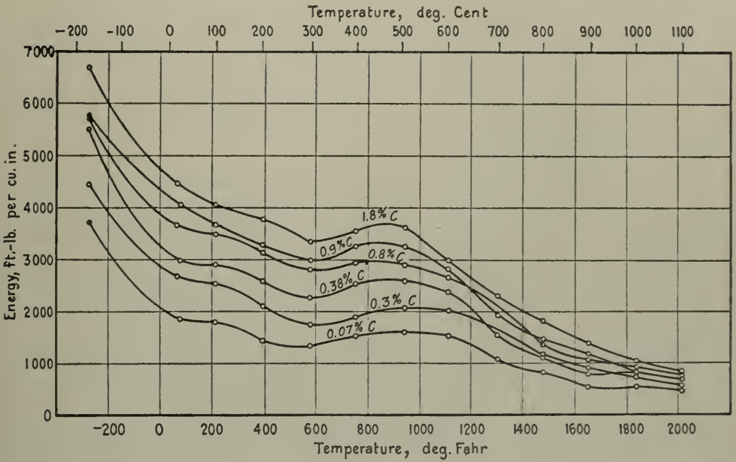

Fig. 12.—Loads Required at Various Temperatures to Reduce the Height of Rolled Carbon-Steel Cylinders (With Ratio of Length to Diameter of 1) by 20 per cent When the Force is Applied at 6.56 ft. (2 meters) per second [Robin (71)].

"The resistance to crushing of a straight steel with circular base diminishes when the ratio of its depth to the diameter of its base increases. The law which correlates this resistance with the relative dimensions of cylinders is represented graphically by the hyperbolic paraboloid. In cylinders with constant dimensions of the base and with increasing depths the resistance to crushing diminishes hyperbolically; in cylinders of constant depth but increasing diameter, the resistance to crushing increases in proportion."

"The rate of testing influences the resistance of metals to crushing. As in the case of a number of different blows it acts in opposite ways according as it is a question of hard and elastic metals or soft metals. At each temperature of crush in any metal the rate of speed produces specific variations in the numerical results."

"The resistance to crushing (of carbon steels) which is relatively considerable at liquid air temperatures, −310° F. (−190° C.) diminishes very rapidly up to 30° F. (0° C.) and then slowly up to 570° F. (300° C.) where the minimum resistance is found. The resistance increases reaching a maximum at about 930° F. (500° C.) followed by a rapid fall at 1560° F. (850° C.) and a very slow fall at higher temperatures. [Refer to Fig. 12.] Lack of cohesion in steels containing high percentages of carbon and the intervention of fusion in soft steels restrict the experiments reducing the resistance to crushing to an exceedingly low value."

Robin further pointed out that "interstrained" steels give more marked variations in crushing resistance than do the same steels after annealing; on the other hand, phosphorus diminishes the variations but "increases the value in common, generally speaking, with other elements dissolved in iron."

"Pearlitic steels undergo the same variations as carbon steels; variations in resistance to crushing may be greatly reduced or even obliterated by the presence of a sufficient amount of an element in solution, such for example, as chromium.

"Martensitic steels yield a decreasing curve which possesses neither maximum nor minimum; the greatest fall in resistance commences at 930° F. (500° C.).

"Austenitic steels vary little in their resistance to crushing up to about 1000 or 1100° F. (550 or 600° C.). The resistance to crushing increases considerably at liquid-air temperatures. Starting from 30° F. (0° C.), the curve is generally rectilinear up to about 1110° F. (600° C.) where the most important fall in resistance occurs. Special steels containing the free carbide and the high-speed steels investigated behave similarly. Their resistance at ordinary temperatures and particularly at about −310° F. (−190° C.) is, generally speaking, high. Some steels preserve a high degree of resistance to crushing at high temperatures, a resistance much greater than that of carbon steels. The presence of nickel favors this resistance at high temperatures."

In comparing the static and dynamic tests of steels at various temperatures, Robin pointed out that:

"The static tensile and hardness tests correspond with one another. Compression appears to indicate corresponding variations: the rate of testing affects the observed results at higher temperatures up to a limit which apparently cannot in practice be exceeded and relates to shocks of any rate or intensity whatever. Brittleness as the result of static effects appears to occur at 570° F. (300° C.) but brittleness under shock is practically in the neighborhood of 930° F. (500° C.).

"The properties of steel, so far as the dynamic and static effects are concerned, vary in totally different ways according to the temperature and according to the nature of the steels. The correlation of these effects at the normal temperature in the case of certain steels appears, therefore, to be due purely to coincidence."

IMPACT TESTS

The results obtained by Reinhold(113), Charpy(97), Guillet(59) and more recently Langenberg(200, 201) will serve to show the effects of temperature variations upon the impact resistance of steels as determined on notched bars. Representative results are shown graphically in Figs. 13 and 14.

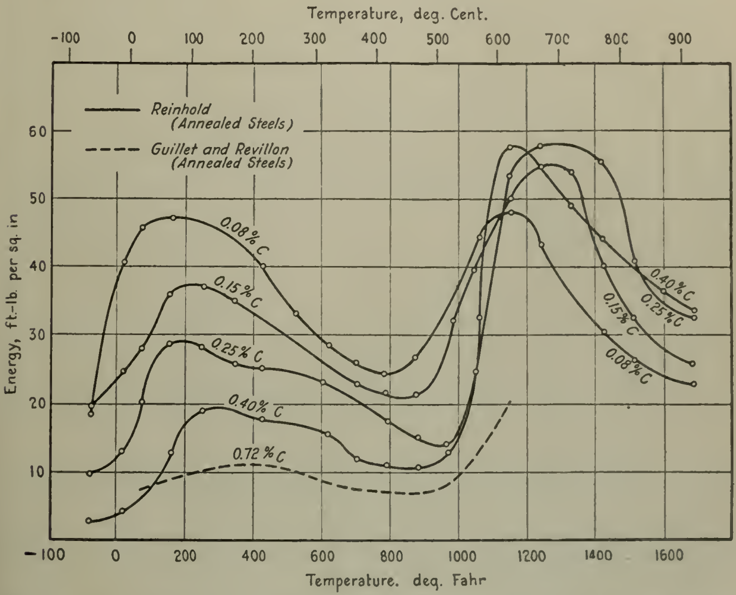

FIG. 13.—Notched-Bar Impact Resistance of Carbon Steels at Various Temperatures.

Refer to bibliography, items (59) [Guillet and Revillon (Guillery test)] and (113) [Reinhold (Charpy test)]

The general form of the impact energy – temperature curves is quite similar for the majority of steels tested. As the temperature is progressively raised from about −100° F. (−75° C.) the absorbed energy increases and reaches maximum values in the range 150 to 400° F. (65 to 205° C.); it then decreases. According to the results obtained by Reinhold, Guillet and Charpy, a second rise in impact resistance begins in the neighborhood of 800 to 1000° F. (425 to

540° C.) and is followed by maximum values which in general are greater than the first maximum between 150 and 400° F. (65 and 205° C.). As the temperature is raised above about 1200 to 1400° F. (650 to 760° C.) the absorbed energy decreases rapidly.

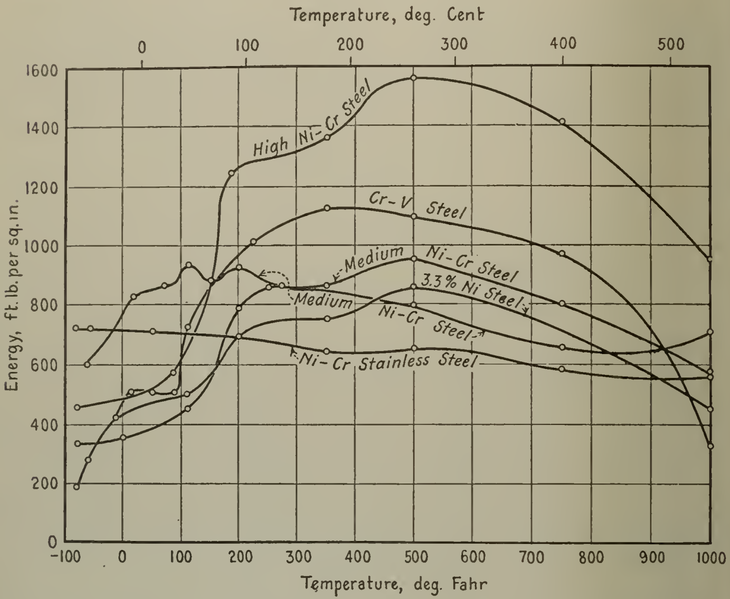

FIG. 14.—Notched-Bar Impact Resistance (Charpy Test) of Some Alloy Steels at Various Temperatures [Langenberg (201).]

High-nickel-chromium steel: 0.39 per cent C; 3.44 per cent Ni; 1.58 per cent Cr. 1450° F. (790° C.) oil; tempered 1150° F. (620° C.).

Chrome-vanadium steel: 0.38 per cent C; 0.79 per cent Cr; 0.15 per cent V. 1600° F. (870° C.) oil; tempered 1150° F. (620° C.).

Medium-nickel-chromium steel: 0.21 to 0.36 per cent C; 1.93 per cent Ni; 0.99 per cent Cr. Annealed at 1650° F. (900° C.) (upper curve) 1580° F. (860° C.) oil; 1400° F. (760° C.) oil; tempered 500° F. (260° C.) (lower curve).

Nickel-Chromium stainless steel: 0.38 per cent C; 23.75 per cent Ni; 7.08 per cent Cr. Annealed at 1290° F. (700° C.).

3.30-per-cent nickel steel: 0.31 per cent C; 3.30 per cent Ni. 1515° F. (825° C.) oil; tempered 1110° F. (600° C.).

These changes appear to be quite generally characteristic of the majority of steels for which data are available, but the magnitude of the observed effects is dependent to a large degree upon composition, previous mechanical and thermal treatments and upon the methods used in the test. The most notable exception is the high nickel-chromium steel containing also about 1.5 per cent silicon, tested by

Langenberg. In this case the absorbed energy shows a very gradual and comparatively small decrease as the temperature is raised from −80 to 1000° F. (−60 to 540° C.).

Attention has already been called to the low ductility in steels in the neighborhood of "blue heat" (400 to 600° F.) (205 to 315° C.) as shown in both tension and torsion tests. This effect is apparently distinct from and not accompanied by brittleness, as the energy absorbed in the notched bar impact tests does not show low values in the specified temperature range.

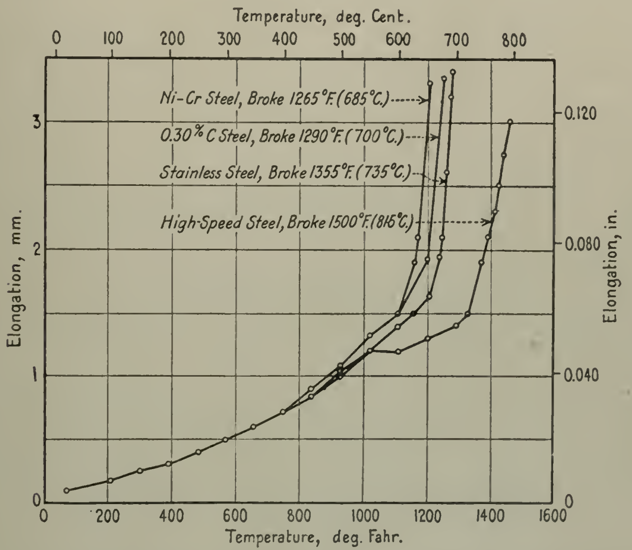

Fig. 15.—"Flow" of Various Steels Under a Static Load of 19,000 lb. per sq. in. (8.5 tons per sq. in.) with Rising Temperature [Dickenson (172).]

Composition and treatment of the various steels are given in Table II.

Langenberg has pointed out and special consideration should be given to the marked influence on impact resistance of ordinary atmospheric temperature variations. Also steels and treatments giving highest impact resistance at 70° F. (20° C.) do not necessarily show the same degree of superiority at higher or lower temperatures and in quite a number of cases the order is reversed. A similar condition is observed in the short-time tension tests and shows the need for readjustment in methods of design of equipment for high or low temperature service.

Another feature of special interest is the superior resistance to impact of the commercial nickel-chromium steels compared to $3\frac{1}{2}$-per-cent nickel steel and likewise the superiority of chromium or chromium-vanadium steels compared to nickel-chromium steel.

The available impact tests show, among other things, that chromium is highly beneficial in the quantities ordinarily used and in comparison with the other alloying elements at present employed in commercial steels appears to "toughen" as well as "stiffen" the resulting metal in those temperature ranges in which composition is of prime importance as compared to heat treatment.

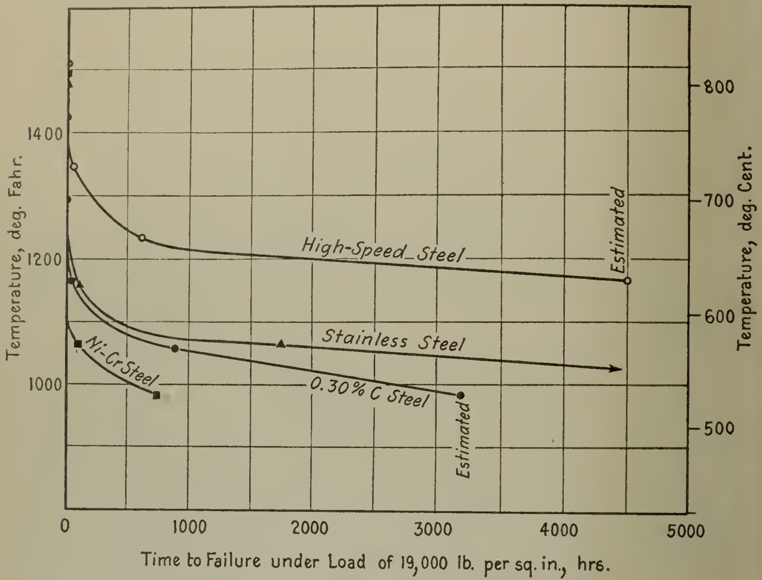

FIG. 16.—Time Required to Produce Failure in Various Steels at Different Temperatures Under a Load of 19,000 lb. per sq. in. (8.5 tons per sq. in.) [Dickenson (172)].

Composition and treatment of the different steels are given in Table II.

LONG-TIME OR "FLOW" TESTS

Mention has already been made in this report of the importance of the time factor in testing metals at high temperatures. In 1919, Chevenard(124) published results obtained under sustained loading on an air-hardening nickel-chromium steel and among other things gave

TABLE II.—LIMITING TEMPERATURES SET BY DICKENSON (172) AT WHICH A LOAD OF 19,000 LB. PER SQ. IN. CAN BE SUSTAINED IN BOTH SHORT AND LONG-TIME TENSION TESTS.

Type of Steel	Heat Treatment[a]	Maximum Temperature to which Steel will withstand Stress of 19,000 lb. per sq. in.			
		For Short Duration of Loading[b]		For Considerable Time without Sensible Deformation	
		deg. Fahr.	deg. Cent.	deg. Fahr.	deg. Cent.
0.30-per-cent carbon steel	1560° F. (850° C.) oil; tempered at 1065° F. (575° C.)	1425	775	930	500
0.45-per-cent carbon steel	1600° F. (870° C.) water; tempered at 1110° F. (600° C.)	1480	805	840	450
Nickel-chromium steel, 0.25 per cent C; 3.6 per cent Ni; 0.6 per cent Cr	1525° F. (830° C.) oil; tempered at 1110° F. (600° C.)	1470	800	970	520
Stainless steel, 0.26 per cent C; 14.7 per cent Cr; 0.6 per cent Si; 0.4 per cent Ni	1700° F. (925° C.) oil; tempered at 1200° F. (650° C.)	1650	900	1065	575
High-speed steel, 0.6 per cent C; 17.4 per cent W; 4.0 per cent Cr; 0.7 per cent V	Annealed 1470° F. (800° C.)	1770	965	1110	600

[a] Fahrenheit temperatures given to nearest 5° in conversion from Centigrade scale.
[b] This refers to the tensile strength values.

TABLE III.—COMPARISON OF SOME DATA IN BOTH LONG AND SHORT-TIME TENSION TESTS AT HIGH TEMPERATURES.

Steel	Heat Treatment[a]	Temperature	
		deg. Fahr	deg. Cent.
MAXIMUM TEMPERATURE AT WHICH STEEL WILL SUSTAIN A STRESS OF 19,000 LB. PER SQ. IN. FOR LONG PERIODS WITHOUT SENSIBLE FLOW[a]			
0.30-per-cent carbon steel	1560° F. (850° C.) oil; tempered 1065° F. (575° C.)	930[b]	500[b]
0.45-per-cent carbon steel	1600° F. (870° C.) water; tempered 1110° F. (600° C.)	840[b]	450[b]
Nickel-chromium steel, 0.25 per cent C; 3.6 per cent Ni; 0.6 per cent Cr	1525° F. (830° C.) oil; tempered 1110° F. (600° C.)	970[b]	520[b]
Stainless steel, 0.26 per cent C; 14.7 per cent Cr; 0.6 per cent Si; 0.4 per cent Ni	1700° F. (925° C.) oil; tempered 1200° F. (650° C.)	1065[b]	575[b]
High-speed steel, 0.6 per cent C; 17.4 per cent W; 4.0 per cent Cr; 0.7 per cent V	Annealed 1470° F. (800° C.)	1110[b]	600[b]
TEMPERATURE AT WHICH A PROPORTIONAL LIMIT OF 19,000 LB. PER SQ. IN. IS SHOWN IN THE SHORT-TIME TENSILE TEST[a]			
0.33-per-cent carbon steel	1555° F. (845° C.) water; tempered 1005° F. (540° C.)	790[c]	420[c]
Nickel-chromium steel, 0.39 per cent C; 3.1 per cent Ni; 0.9 per cent Cr	Air cooled from 1560° F. (850° C.)	930[d]	500[d]
Stainless steel, 0.31 per cent C; 12.8 per cent Cr	1750° F. (955° C.) oil; tempered 1210° F. (655° C.)	1065[e]	575[e]
High-speed steel, 0.64 per cent C; 15.6 per cent W; 4.8 per cent Cr; 0.2 per cent V; 0.2 per cent Mo	Annealed	860[f]	460[f]

[a] Fahrenheit temperatures given to nearest 5° in conversion from Centigrade scale.
[b] From data reported by Dickenson (172).
[c] From data obtained by one of the authors.
[d] From data reported by French (153).
[e] From data reported by French (180).
[f] From data reported by Welter (164).

definite values for the rate of flow for various loads at different temperatures. More recently Dickenson(172), following the same principles, reported results obtained in both short-time and prolonged tension tests of various steels. Two carbon steels, a nickel-chromium steel, stainless (13 per cent chromium) and high-speed steels were investigated and results are reproduced in part in Figs. 15 and 16.

Table II is also taken from Dickenson's report and shows quite clearly that the ordinary tensile strength values at high temperatures give no direct indication either of the limiting temperatures up to which fixed loads can be maintained without sensible flow or the limiting loads which can be sustained at various temperatures.

While freely condemning the short-time tension test as being worthless for use by designing engineers, Dickenson unfortunately neglected the only factors which might show a direct relation to the results obtained so laboriously in the long-time tests. No attempt was made to determine proportional or elastic limits and the stress-strain relations in the ordinary tests or to correlate existing data of this type with the limiting values determined under prolonged loading.

In Table III are given the limiting temperatures determined by Dickenson at which a load of 19,000 lb. per sq. in. (8.5 tons per sq. in.) can be sustained for long periods by each of the five steels without sensible deformation, and also the temperature at which a proportional elastic limit of 19,000 lb. per sq. in. is shown in the short-time tension test. These latter values were, of necessity, collected from various sources so that many variables are introduced when comparisons are attempted, such as, for example, individual heat characteristics of the steels, variations in chemical composition and heat treatment, methods of test, etc. Despite these variations the limiting temperatures determined from the stress-strain relations in the short-time tests are comparable to those deduced from the prolonged loading. In fact in all but one case the former values are somewhat lower than the latter. For the two stainless steels which are quite similar in composition and heat treatment identical values are obtained.

It is not intended to give the impression that proportional limits determined by methods so far employed can give as accurately as sustained-loading tests the limiting loads or temperatures for various steels, but at least the comparisons cited point to the possibility of obtaining from the stress-strain relations in a short-time test with slow rates of loading quite satisfactory information for most practical purposes. Dickenson's values may be accepted as quite accurate, but it should be kept in mind that they are based on individual heats tested under specific conditions. Similar tests carried out on additional heats of each type of steel would undoubtedly show variations which might possibly be as great as the differences shown by the two methods in Table III.

SPECIAL HIGH-TEMPERATURE PROPERTIES AND TESTS

THERMAL EXPANSION

Thermal expansion of ferrous metals is of particular interest in the design and installation of equipment for high-temperature service and there are included in the appended bibliography references relating to such data for irons and steels. It may be well to point out that the average coefficient for annealed structural carbon and the majority of current commercial structural alloy steels recently tested by Souder(193, 194) is between about 6.5×10^{-6} and 7.5×10^{-6} parts per unit length per 1° F. over the temperature range 75 to 570° F. (25 to 300° C.); in the range from 570 to 1110° F. (300 to 600° C.) it is between 8.0×10^{-6} and 9.3×10^{-6}. Among the principal exceptions are Invar and some of the related high-nickel steels which have very low expansion coefficients at slightly elevated temperatures but show exceptionally high values in the neighborhood of 750 to 1110° F. (400 to 600° C.). Likewise stainless steel (13 per cent chromium) shows a somewhat lower expansion than the representative values given above. The sample tested by Souder had an average of 6.1×10^{-6} from 75 to 570° F. (25 to 300° C.) and 7.4×10^{-6} in the range from 570 to 1110° F. (300 to 600° C.).

"GROWTH" IN CAST IRONS

Cast irons, as is well known, are subject to permanent changes in volume upon repeated heating and as a result their field of usefulness has been restricted. This effect, which is generally an increase in volume for commercial materials and commonly called "growth," is not only dependent upon temperature and time but also upon composition. According to Rugan and Carpenter(65)[1] white irons shrink and gray irons grow, but in white irons containing appreciably more than 3 per cent carbon there is a tendency to deposit temper carbon upon prolonged heating and the metal will then tend to grow. An alloy of practically constant volume under repeated heating at 1650° F. (900° C.) was found to be a white iron containing about 3 per cent of carbon and only small quantities of other constituents and in particular less than 0.2 or 0.3 per cent of silicon.

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[1] Attention should be called to the very early studies of the "growth" in cast irons by A. E. Outerbridge, Jr., (51) though the more recent experiments cited better serve the purposes in view for this paper.

Carpenter(65) stated that phosphorus tends to diminish "growth" and that if 0.3 per cent is present, growth is lessened by about 3 per cent. The amount of sulfur present in commercial cast irons is not usually sufficient to have more than a minor influence. Manganese is one of the most important elements to be considered and not only retards the rate of growth but in the majority of cases diminishes the absolute amount. The effect of dissolved gases is negligible in the presence of more than 3 per cent of silicon, but may cause a growth of 1 to 2 per cent in irons containing 1.75 to 3.0 per cent of this element and at least 10 per cent when silicon does not exceed 1 per cent.

As a result of his investigations, Carpenter recommended the use of a "semi-steel" containing about 2.6 per cent of carbon, 0.6 per cent of silicon and 1.6 per cent of manganese for annealing ovens, rolls, fire bars, high-pressure steam valves and turbine casings whose growth, when made from gray irons, is so objectionable a feature. Such metal showed no growth after 150 heatings to high temperatures but on the contrary a slight contraction of about 0.13 per cent.

CHEMICAL STABILITY

In addition to suitable mechanical properties, chemical stability or, as described by Chevenard(170), "chemical inertness" is an important factor in the selection of metals for use at any temperature. It is not considered within the scope of this paper to attempt even a partial review of the large mass of literature relating to corrosion at ordinary or low temperatures but mention should be made of the extensive bibliography relating to this subject recently prepared by Van Patten(207).

While it is well recognized that certain alloys are generally more resistant to chemical changes than others, the greater part of published data on the high temperature stability of ferrous metals is concerned with failures or observations made under specific laboratory or service conditions. Few comparisons of alloy steels at relatively high temperatures have been recorded. Because of this and the fact that many variables are encountered in different types of service only brief reference will be made to typical effects.

Intercrystallin Deterioration.—Failures have not been uncommon in iron or steel parts due to intercrystallin attack resulting in what has been called intercrystallin brittleness. Stress, which may be either internal or external but probably restricted in intensity, nature and distribution, is a necessary condition for such selective attack. However, the active agents producing intercrystallin brittleness may vary widely. Thus in power-plant installations the embrittlement of boiler steels may be the result of reactions with dissolved alkaline substances in the feed water(118). In a case recently brought to the attention of the authors, embrittlement was observed in wrought-iron stirring rods immersed in molten copper and was accompanied by intercrystallin penetration of the copper.

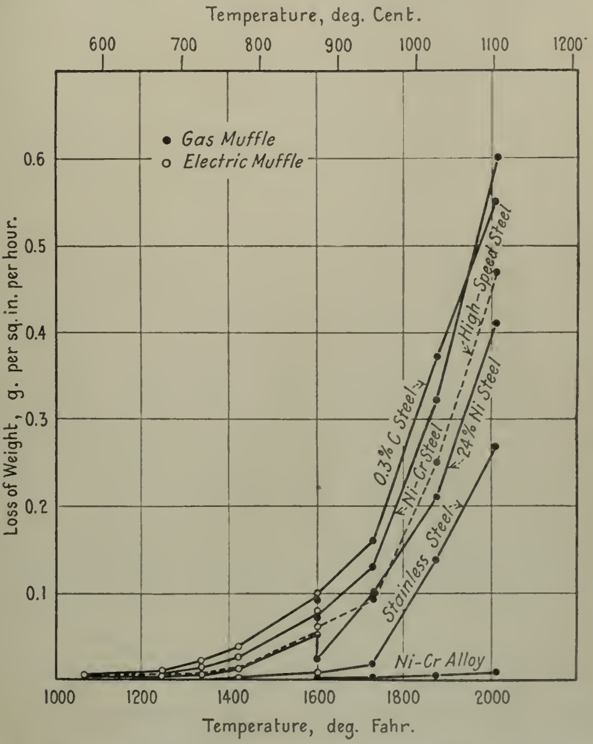

FIG. 17.—Comparison of the Rate of Scaling of Various Steels and a Cast Nickel-Chromium Alloy at Elevated Temperatures [Dickenson (172)].

Composition and treatment of the steels are given in Table II. The nickel-chromium alloy contains 0.54 per cent C; 0.73 per cent Si; 0.10 per cent Mn; 69.9 per cent Ni; 15.5 per cent Cr. Tests carried out in either gas-fired or electric furnaces as indicated.

The intercrystallin cracking of mild steel in caustic soda solutions has been attributed to the weakening of grain boundaries due to hydrogen absorption by the intercrystallin material alleged by one school of metallurgists to be amorphous. Jones(167) has shown that solutions of nitrates also yield a product having a selective action on the intercrystallin material and suggests that this may be nitrogen or an oxide of nitrogen. However, intercrystallin fracture of metals may possibly occur, according to Hanson(167), "as a result solely of the stresses but corrosive agents might act in accelerating them" and likewise cases are cited where material, relatively free from stresses, has developed intercrystallin fracture due to cementite envelopes, etc.

It is not intended to discuss all possible causes of intercrystallin brittleness and fracture but merely to point out (1) that such effects are observed in steels under a variety of conditions in which stress and corrosive agents have been present, (2) that few data are available for comparison of various ferrous alloys and (3) that with increasing demands upon materials for high-temperature service, both with respect to stresses and temperatures, further attention must be given to this important subject.

Oxidation of Steels.—The relative resistance to oxidation of alloy steels in air has recently been studied by Aitchison(123) and Dickenson(172). As the result of extensive tests of carbon, chromium, nickel, nickel-chromium and tungsten steels, the former concluded:

> "That the high-chromium steels present the greatest resistance to scaling at high temperatures of any of the steels. Those of the "stainless" type (13 per cent chromium) give a very high resistance whilst those containing about 7 per cent of chromium give a very fair resistance though not quite so good as that of the stainless steels. In the latter case, however, the scale is more adherent than in the case of the stainless steel type."
>
> "That the nickel-chromium steels (ordinary structural types) scale to a greater extent than do the steels of any of the other types."
>
> "That the tungsten steels scale comparatively little up to temperatures of about 1560° F. (850° C.), but beyond that they are liable to scale very considerably."

Results obtained by Dickenson(172) are partially summarized in Fig. 17 and likewise show the superiority of the stainless steel in comparison with carbon, ordinary nickel-chromium, high-nickel and high-speed steels. However, an iron alloy containing high proportions of nickel and chromium is much superior to stainless steel. Dickenson also pointed out a marked difference in the formation of the scale produced in steels containing nickel and those without appreciable quantities of this element. The former all showed the characteristic "double scale" described by Stead(115) in which the lower layer contains a large proportion of metal.

TREND OF DEVELOPMENT OF "HEAT-RESISTING" ALLOYS

The foregoing sketch of available data, while incomplete, shows clearly that irons and steels have serious limitations for high-temperature service. In the case of cast and malleable irons and semi-steels this is further substantiated by the recommendations of one manufacturer of power plant equipment:[1]

> "Cast iron is recommended for a total temperature of 500° F. (260° C.) when the pressure does not exceed 25 lb. gage and for 100° F. (40° C.) when the gage pressure is not greater than 75 lb. Malleable iron and semi-steels are recommended for temperatures up to 500° F. (260° C.) when the pressure does not exceed 200 lb. gage; at higher temperatures and pressures cast or forged steels are recommended."

As already indicated, the composition and treatment of steels may be varied to meet specific requirements at temperatures above 500° F. (260° C.). However, it is also evident from the described data that all steels "weaken" with considerable rise in temperature. While this weakening may be delayed by additions of relatively large proportions of such elements as chromium, the resulting product retains, in this respect at least, the characteristic properties of the iron which forms the largest part of the alloy, and steels would not generally be expected to stand up under fairly high stress at temperatures exceeding about 1200° F. (650° C.). Thus for service at higher temperatures it would appear necessary to seek alloys in which the iron plays a secondary rôle instead of forming the largest part of the product.

In this connection it will be of interest to cite briefly the result of experiences encountered with the direct synthetic ammonia process as summarized by Vanick.[2]

> "The fixation of nitrogen by the synthetic ammonia processes requires metal tubes and containers capable of conveying or holding corrosive gas at high temperatures and high pressures. A gas-proof, forgeable, machineable corrosive-resisting and heat-resisting material is required. The Fixed Nitrogen Research Laboratory of the Department of Agriculture has completed an extensive investigation of plain carbon and alloy steels that might be applied to this service.
>
> "Of the commercially obtainable alloy steels in the 0.30 to 0.40-per-cent carbon range, those containing chromium or tungsten or both elements showed a superior resistance to deterioration over other alloy steels. A series of chromium-vanadium steels containing up to 21 per cent chromium showed an improvement in resistance to deterioration which increased with the percentage of chromium in the alloy. For the purposes which the laboratory had in view, a 2½-per-cent chromium steel was selected as suitable for the type of service demanded of a metal in the direct synthetic ammonia process. These results apply to the special conditions of test representing 100 atmospheres pressure of synthetic mixtures at 930° F. (500° C.). No significant improvement in tensile properties at elevated temperatures was obtained with these steels.

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[1] Data obtained from correspondence.

[2] This summary was prepared at request of the authors by Mr. J. S. Vanick, formerly of the Fixed Nitrogen Research Laboratory, U. S. Department of Agriculture.

"Long before this position in the development of materials had insured temporary security, new achievements in the same field of chemistry were requiring better materials to hold the same gases at super-pressures and perhaps super-temperatures, with respect to earlier processes. Pressures which can be held at ordinary temperatures exert stresses at the operating, elevated temperatures that would correspond to or exceed the limit of elasticity for practically all steels and ferrous alloys. So important has high-temperature strength become for this service that the property of resistance to corrosion which had thus far been associated with it, may be subordinated; partly because most of the elements which possess the property of strength or coherence at elevated temperatures also possess, in this case, a superior resistance to corrosion or deterioration."

"New investigations are leading into alloys of the inelastic type; alloys which possess a yield point at ordinary temperatures that closely approaches the ultimate strength. At elevated temperatures some plasticity would be expected which would not necessarily imply elasticity. At present these alloys are expensive, unmachineable, must be cast to shape with the difficulty that attends viscous fusions, and in the present state of development improve the high-temperature strength very slightly. For service as tubes or containers for gas under pressure, such defects as porosity and segregation delay their acceptance."

"Work on these important alloys will clear many of the obstructions now encountered in their preparation and lead to new developments in the strength-at-high-temperature field."

Some of the features pointed out by Vanick are in substantial agreement with experiences encountered in France in the production of ammonia by the Claude process. The development of materials in this case is reported by LeChatelier[1] as follows:

"Mr. Claude had begun his experiments with a mild steel tube under a pressure of a thousand atmospheres, water-cooled and heated internally by a helix through which was passed electric current. He [Professor LeChatelier] had made the suggestion that as iron possessed considerable tensile strength at 750° F. (400° C.) it would be sufficient for the purpose to plunge the tube into a bath of lead and thus reduce considerably the consumption of electric energy. From the first the experiment succeeded, and Mr. Claude was able to obtain from the outlet of his tube liquid ammonia, the problem being thus apparently solved. Unfortunately, after a run of six hours the plant exploded. . . . Experiments made under the same pressure of a thousand atmospheres and at a temperature of 1110° F. (600° C.) on iron wires showed that the nitrogen had no action but that the hydrogen caused rapid alteration in the metal similar to that observed in the case of the tube referred to above. It was necessary, therefore, to find a metal which would resist the action of hydrogen. . . . Mr. Chevenard suggested in the first instance a steel having a composition similar to that of high-speed steel. . . . That steel underwent without difficulty a pressure of a thousand atmospheres at 1110° F. (600° C.). It was no longer necessary to resort to internal heating: the heat evolved by the reaction was sufficient to a great extent to maintain a temperature of 1110° F. (600° C.) at

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[1] Discussion of report by Dickenson (172).

the point where the external cooling was not too great. Once again it was assumed that a final solution of the problem had been found but after a hundred hours of working the tube again exploded."

"Mr. Chevenard then suggested the use of another 'steel' having the following composition: Nickel, 60 per cent; iron, 25 per cent; chromium, 12 per cent; manganese, 2 per cent; carbon, 0.5 per cent. The tubes from that metal yielded excellent service and tubes of larger dimensions were therefore ordered capable of being employed in normal manufacture. It was found impossible to forge the large ingots and necessary to employ the metal as cast. The tubes behaved, nevertheless, very well in service and some of them had already been in use for five thousand hours."

TABLE IV.—SOME "HEAT-RESISTANT" ALLOYS NOW IN USE OR PROPOSED FOR HIGH TEMPERATURE SERVICE OF VARIOUS TYPES.[1]

(Approximate Type Compositions Unless Otherwise Specified)

Manufacturer or Name	Chemical Composition, per cent									Remarks
	C	Mn	Ni	Cr	W	Co	Si	Fe	Cu	
GROUP I. STEELS										
I (*a*) Stainless iron ..	Under 0.12	...	....	11 to 14	....	..	...	....	..	
(*b*) Stainless steel..	0 2 to 0.4	...	....	11 to 14	....	..	...	....	..	
(*c*) Manufacturer A	Under 0.8	...	....	18 to 20	....	..	...	....	..	
(*d*) " B	0.5	...	....	25	....	..	0.4	....	..	
(*e*) " C	0.3	...	....	28 to 30	....	..	...	....	..	
(*f*) " D	0.30	0.30	....	19.0	3.0	..	2.75	....	..	P, 0.02 S, 0.02 Actual analysis
(*g*) " E	0.3	...	....	20	....	..	...	....	1	
(*h*) " F	0.4	0.23	15.3	16.0	....	..	3.22	....	..	Actual analysis
(*j*) " G	1.75 to 2.00	...	5	20	....	..	...	....	..	
(*k*) " H	0.4	...	21	7.5	....	..	1.5	....	..	
GROUP II. NICKEL-CHROMIUM-IRON-BASE ALLOYS										
II (*a*) French patent 469, 929......	0.3 to 1.0	1 to 5	50 to 80	8 to 25	0.5 to 8.0	..	...	.....	..	Tungsten may be partially replaced by Molybdenum
(*b*) French Alloy "ATG"......	....	...	60	10	4	..	...	Remainder	..	See text and Fig. 18
(*c*) French alloy....	0.5	2	60	12	....	..	...	25	..	See text
(*d*) Manufacturer J.	....	...	62	11	....	..	...	25	..	
(*e*) Manufacturer J, K, L, M, N...	0.5	2	68	17	....	..	1	10.75	..	Mo, 0.75
(*f*) Manufacturer G	0.2 to 1.25	...	35	15	....	..	...	47	..	
GROUP III. ALLOYS FREE FROM OR LOW IN IRON										
III(*a*) Manufacturer J	....	...	80	20	....	..	...	.....	..	
(*b*) " J	....	3	94	...	....	..	1	.....	..	Al, 2
(*c*) " O	....	...	80	11	....	..	...	6	..	
(*d*) " J	0.2	1.5	83.5	13.5	....	..	0.3	0.5	..	
(*e*) German alloy (Tammann)..	....	...	....	25	....	75	...	.....	..	See text
(*f*) German alloy (Tammann)..	....	...	...	30	....	70	...	.....	..	See text
(*g*) Aluminum-nickel	Under 0.15	0.3	97	....	....	..	0.3	0.5	..	Al, 1.8
(*h*) Manganese-nickel	0.2	3	95+	....	....	..	...	1	..	
(*j*) "A" nickel.....	0.15	0.2	99	....	....	.	...	Remainder	.	

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[1] Copper-nickel and other non-ferrous alloys especially adapted for service at steam temperatures are not considered.

Quite a number of "heat-resisting" alloys are now produced commercially in this country and others have been shown to have desirable properties at very high temperatures. Many of these cannot be called steels or even ferrous alloys and in some cases are practically free from iron but they will be briefly considered to show the present trend in development of metals well adapted for various types of high-temperature service under which ordinary steels fail to meet at least some requirements.

In Table IV, in which is given a partial but representative list of such metals, an arbitrary division has been made depending upon the iron content. The first group comprises steels with relatively large proportions of special elements but containing over 50 per cent of iron; the third group consists of alloys practically free from this element or with proportions up to 4 or 8 per cent in the nature of an impurity; the second is an intermediate group with from about 10 to 50 per cent of iron. Commercial non-ferrous alloys for service at steam temperatures are not considered.

Except in two cases the steels of Group I, Table IV, are low in carbon and are based upon chromium additions of from 11 to 30 per cent. However, they may also contain varying amounts of one or more of the elements, nickel, tungsten, silicon and copper and such additions may be expected to modify the properties obtained. Steels similar to No. I (*h*) have exceptionally good resistance to oxidation at high temperatures and have been discussed by Johnson(108).

The alloys in Group II are primarily nickel-chromium-iron alloys with or without additions of tungsten, manganese, silicon and molybdenum and in the majority of cases are quite close to or within the limits given under No. II(*a*), Table IV. They have been used to advantage for a variety of purposes including furnace parts, containers employed in the heat treatment of metals, etc. One of these, as has already been indicated, has been used in France for tubes employed in production of ammonia by the Claude process. The mechanical properties of two of the alloys in this group are shown in Fig. 18 in comparison with heat-treated stainless steel and a chromium-molybdenum structural steel.

In addition to alloys of nickel with chromium, manganese, aluminum and silicon, Group No. III contains two cobalt-chromium combinations, mentioned by Tammann,[1] which are reported to have very desirable mechanical properties in the neighborhood of 1300 to 1500° F. (705 to 815° C.). Alloy No. III(*e*), Table IV, showed an elastic limit of about 40,000 lb. per sq. in. at 1470° F. (800° C.) and No. III(*f*)

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[1] Refer to discussion of Dickenson's report (172).

about 65,000 lb. per sq. in. at 1330° F. (720° C.). Nickel, or alloys containing very large proportions of this element, as shown in Group III, have excellent resistance to oxidation at temperatures up to 1830° F. (1000° C.) in atmospheres relatively free from sulfur but not high strength when considering sustained loads. Some, as in the case of Nos. III(*a*), (*b*) and (*c*) have special electrical properties which make them particularly useful.

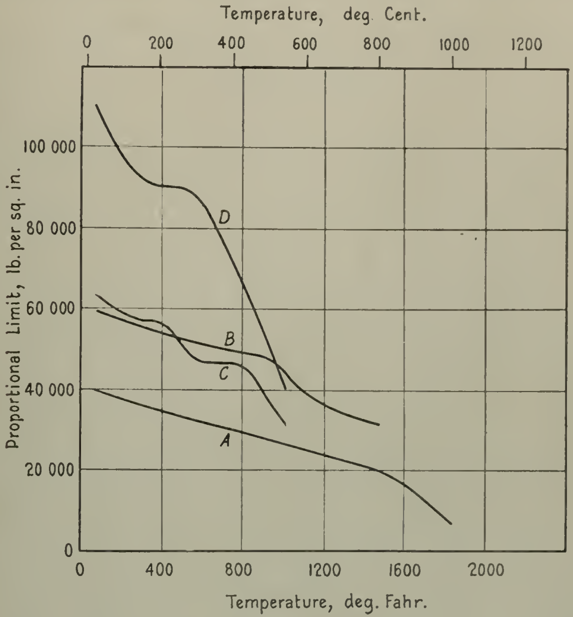

FIG. 18.—Effect of Temperature on the Proportional Limit of Chromium-Molybdenum and Stainless Steels and Two Nickel-Chromium-Iron Alloys (Collected from Various Sources).

A—Nickel-chromium-iron alloy containing approximately 0.8 per cent C; 35 per cent Ni; 15 per cent Cr. Tested as cast. Data obtained by the authors.

B—Nickel-chromium-iron-tungsten alloy containing about 60 per cent Ni; 10 per cent Cr; 4 per cent W; 25 per cent Fe [Guillet (100)].

C—Steel containing 0.27 per cent C; 0.99 per cent Cr; 0.41 per cent Mo. Oil quenched from 1550° F. (845° C.); tempered at 1110° F. (600° C.). [French and Tucker (196)].

D—Stainless steel containing 0.31 per cent C; 12.75 per cent Cr. Oil quenched from 1750° F. (955° C.); tempered at 1250° F. (675° C.) [French (180)].

Note the rapid decrease in the proportional limit of the steels above 800° F. (425° C.) as compared with the two nickel-chromium-iron alloys.

In conclusion, mention should be made of the possible developments in the use of coated metals for high-temperature service. Aluminum (calorizing) and chromium (chromizing) coatings appear to offer promising developments in this field.

AVAILABLE DATA ON THE PROPERTIES OF NON-FERROUS METALS AND ALLOYS AT VARIOUS TEMPERATURES

Clair Upthegrove[1] and A. E. White[2]

Introduction

The physical properties of the non-ferrous metals at elevated temperatures have attracted the attention of relatively few investigators. While considerable study has been given to the properties of iron and steel at elevated temperatures, non-ferrous materials have received but little attention until very recently. Moreover, the present attention given is not in keeping with their importance.

One of the earliest investigations of non-ferrous alloys at elevated temperatures was carried out in 1877 by the British Admiralty at the Portsmouth Dockyard. The test bars were first heated in an oil bath and then transferred as quickly as possible to the testing machine and broken. Even this very crude arrangement gave remarkably accurate results. In 1890, Martens reported, in connection with a series of tests on iron and steel at elevated temperatures, the results of some tests on copper. This seemingly represents the beginning of a series of tests by Rudeloff, Stribeck, Unwin, Charpy, Bach and Le Chatelier. Their investigations of non-ferrous metals were confined mainly to copper, although Rudeloff made a rather extensive investigation of high-manganese bronzes and Delta metal. The results of these were given quite largely in Rudeloff's report on "The Influence of Increased Temperatures on the Mechanical Qualities of Metals."

In more recent years the properties of non-ferrous metals at elevated temperatures have been contributed to very largely by Huntington, Bengough, Hanson, Edwards, Rosenhain, Lea, Doernickel and Trockels in Europe, and by Bregowsky and Spring, Jeffries and Sykes, and very recently by Malcolm in this country. Of this work, both in this country and abroad, a considerable proportion has had as its primary purpose the determination of certain scientific facts rather than physical properties, although the latter have not been ignored. As a result many of the tests have been carried out

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[1] Assistant Professor of Metallurgical Engineering, University of Michigan, Ann Arbor, Mich.

[2] Professor of Metallurgical Engineering, and Director, Department of Engineering Research, University of Michigan, Ann Arbor, Mich.

under very widely varying conditions as to the nature of the material, that is, composition, degree of working or of annealing, size of specimens, method of heating, temperature measurement, nature of atmosphere in which the tests were made, and method and rate of loading. The work of Lea and of the National Physical Laboratory of England on aluminum alloys stands forth as that of well organized and systematic tests, the primary purpose of which is the determination of the physical properties. Similarly, in this country, the work of Bregowsky and Spring, and the more recent investigations of Malcolm, represents work which has had as its primary purpose the determination of the physical properties.

The purpose of this paper is not to present all of the work which has been done on the physical properties of non-ferrous metals at elevated temperatures, but to present as far as possible typical properties for the various metals which have been investigated. In many cases alloys have been investigated by only one individual, or investigators have used materials so widely different in composition as to represent in reality two entirely different alloys. In view of this condition and the limited development of the art of the testing of non-ferrous alloys at elevated temperatures, it has seemed unwise to include values from any other than the original sources. In one case, where the original author has drawn his curves to emphasize certain inflections or critical points the values have been replotted and the curves drawn as average curves. (Figs. 2, 13 and 14.)

No attempt has been made to consider the methods of testing, that being considered beyond the scope of this paper.

COPPER

Copper, though somewhat limited in its field of application at high temperatures, has apparently invited the attention of a number of investigators. Rudeloff (1893–1898), Unwin (1899), Le Chatelier (1901), and Stribeck (1903) made tests on copper at elevated temperatures. The results of these tests were presented by Rudeloff(**27**,**64**)[1] in his official report, "Influence of Increased Temperatures on the Mechanical Qualities of Metals," made to the International Association for Testing Materials in 1909. The results presented, while extending over narrower ranges of temperature than used by later investigators, showed in addition to the actual temperature effects, the influence of composition, of cold working and of the rate of loading. Rudeloff found the tensile strength of cold-worked copper superior to that of annealed copper at the lower temperatures. At higher temperatures this difference disappeared. Tin in copper was

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[1] The boldface numbers in parentheses refer to the papers of the Bibliography appended hereto, page 124.

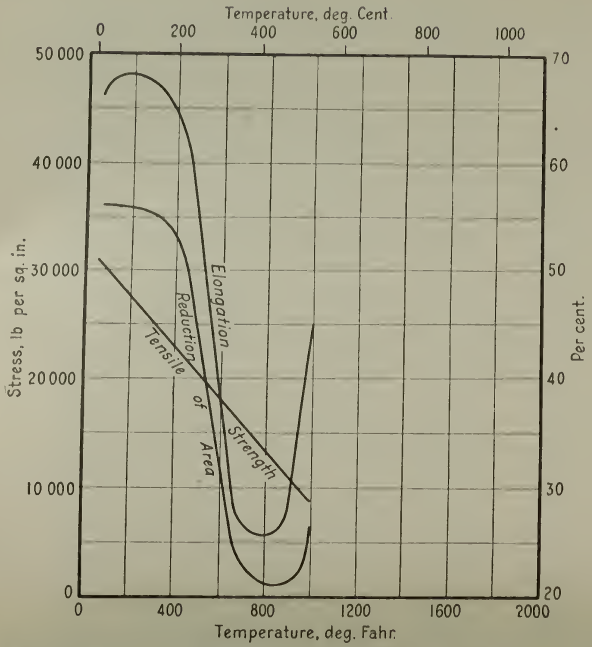

FIG. 1.—Effect of Temperature on Tensile Properties of Electrolytic Copper, According to Huntington(85).

Annealed at 1112° F. (600° C.)

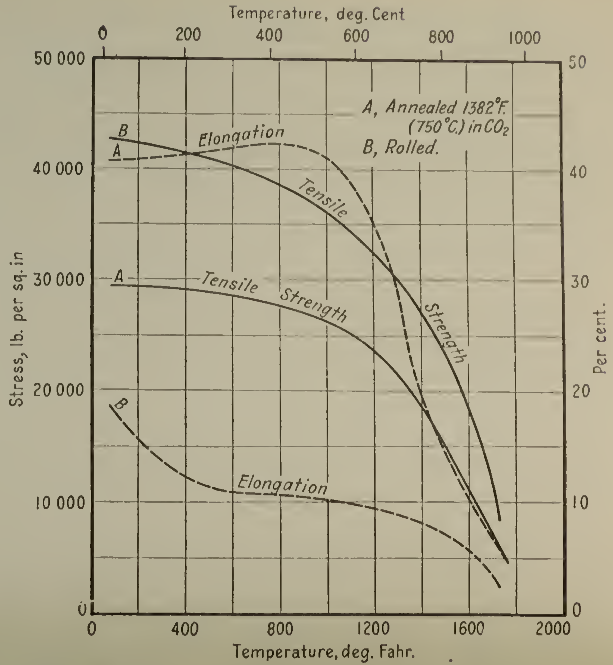

FIG. 2.—Effect of Temperature on Tensile Properties of Electrolytic Copper, According to Bengough and Hanson(96).

Broken in Carbon Dioxide.

found not only to aid in retention of the tensile strength but to increase in a very marked manner the tensile strength at the higher temperatures. Stribeck(48) found lower tensile values but used a slower rate of loading. These tendencies have all been confirmed by the later investigators, though the degree to which these factors influence properties or the temperatures at which the effects are most marked are not always in agreement with the earlier results.

In the period following the presentation of Rudeloff's report and up to the present time, investigations of copper at elevated temperatures have been made by Huntington, Bengough and Hanson, Jeffries, Hughes, Doernickel and Trockels, and others. While the methods of testing used by both Huntington and Bengough have been subjected to considerable criticism, particularly the method of heating used by Huntington and the method of loading employed by Bengough, their results are of decided interest.

The tensile properties of electrolytic copper as determined by Huntington(85) and by Bengough and Hanson(96) are shown in Figs. 1 and 2. In Fig. 3 Bengough's(82) tensile properties of a cold-rolled copper carrying 0.05 per cent arsenic are shown. Annealed electrolytic copper, according to Bengough and Hanson, shows when tested in an atmosphere of carbon dioxide quite different properties than when tested in air. In air, tensile strength falls off rapidly with increasing temperatures, while the elongation decreases somewhat slowly up to 400 to 500° F. (205 to 260° C.) and then very rapidly to a minimum. Tested in an atmosphere of carbon dioxide, both tensile strength and elongation are retained practically undiminished up to temperatures of 950 to 1050° F. (510 to 565° C.). Above these temperatures both tensile strength and elongation decrease rapidly. In the rolled condition, the electrolytic copper shows a slightly greater decrease in strength at low temperatures. The elongation decreases rapidly up to temperatures of 400 to 500° F. (205 to 260° C.), remains unchanged up to 1100 to 1200° F. (600 to 650° C.), followed by a rapid decrease. It will be noted that neither the rolled nor the annealed electrolytic copper shows a reversal in elongation if tested in carbon dioxide. Bengough, however, did obtain a reversal in elongation for cold-rolled copper tested in air (Fig. 3). In his opinion, this marked difference in behavior of the tensile properties of copper at the higher temperatures was due to the influence of arsenic in the copper and the presence of the oxidizing atmosphere. The decrease in elongation between 400 and 500° F. (205 to 260° C.) observed by Huntington and by earlier investigators, it was suggested, might be due to the influence of the annealing.

Jeffries' work(127) on tensile properties of copper wire at temperatures above and below atmospheric temperature are not entirely in agreement with those of Bengough and Hanson. Jeffries used electrolytic copper and an atmosphere of argon for all tests above 400° F. (205° C.). With annealed copper wire a decrease in elongation was observed at 400 to 500° F. (205 to 260° C.) by Jeffries but no indication of a reversal at 800° F. (425° C.), the elongation decreasing continuously. With cold-drawn electrolytic copper, Jeffries shows a decrease in elongation followed by a very rapid increase at a temperature lying between 800 and 900° F. (425 and 480° C.), a change similar to that observed by Huntington for annealed copper.

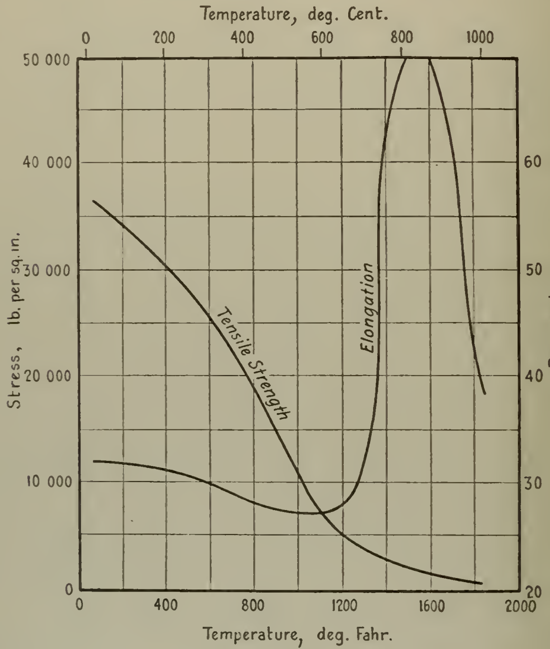

FIG. 3.—Effect of Temperature on Tensile Properties of Copper, According to Bengough(82).

Chemical Composition, per cent: Cu, 99.84; As, 0.05; Mn, 0.08; Fe, trace; S, 0.005.

Although Jeffries' results were obtained on small wires and a faster rate of loading was used by him than by Bengough and Hanson, the regularity with which the reversal in elongation in the neighborhood of 800° F. (425° C.) occurred on the cold-rolled copper, leaves the question of the behavior of cold-rolled electrolytic copper when tested as above somewhat in doubt. Either the results obtained by Bengough and Hanson and by Jeffries are open to question or factors other than the presence of oxygen or arsenic contribute to this difference.

The above variations in the tensile properties of copper at elevated temperatures have been pointed out primarily to show how very readily the tensile properties, particularly the elongation, are influenced by the presence of factors other than the temperature alone. The presence of impurities, oxidizing or non-oxidizing conditions, cold working, the degree of annealing, the rate of loading, method of testing—all may have a very decided influence on the tensile properties, though usually to a greater degree on the elongation.

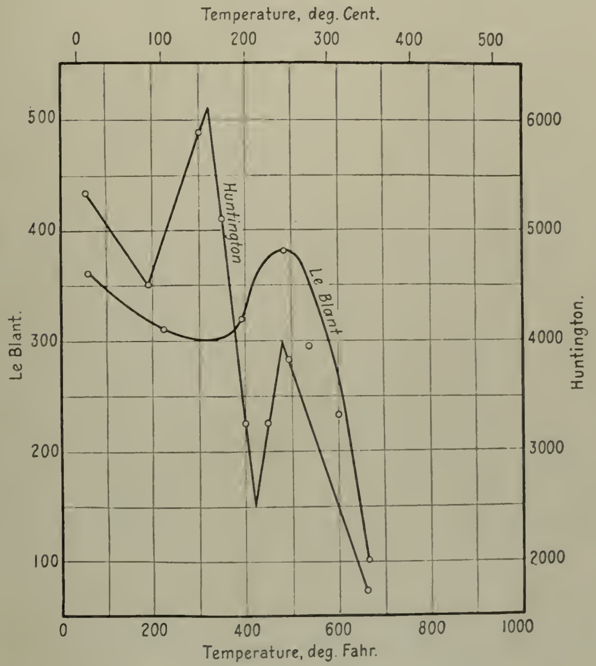

FIG. 4.—Effect of Temperature on Resistance to Alternate Bending of Copper, According to Huntington(107) and Le Blant(34).

For average conditions the changes in tensile properties of copper at elevated temperatures will conform in general to the changes noted by Huntington (Fig. 1). Rolled copper will show a tensile strength superior to that of annealed copper at the lower temperatures. Both tensile strength and elongation differences for rolled and annealed copper will disappear at higher temperatures, or even at lower temperatures if held sufficiently long for an annealing effect to occur.

Additional tests on copper at elevated temperatures which may properly be mentioned are hardness tests by Kürth(62) and Ludwik(112), low-temperature tests by Jeffries(127), alternate stress or bending tests by Huntington(107), modulus determinations by Iokibe and Sakai(154) and crushing tests by Doernickel and Trockels(149).

Kürth(62) has shown the hardness of copper to decrease gradually with increasing temperatures. Confirmatory results have been obtained by Ludwik(112), who also investigated hardness of lead, zinc, aluminum, tin, antimony, cadmium, and bismuth. According to Ludwik the influence of the time of loading becomes very important at higher temperatures, a 15-second and a 300-second loading resulting in a 40 to 50-per-cent difference in hardness values at 900 to 1000° F. (480 to 540° C.). Huntington (Fig. 4) found the resistance to bending stresses decreases very little at temperatures up to 350 to 400° F. (175 to 205° C.). Le Blant(25) in earlier investigations found little decrease up to 500° F. (260° C.). Jeffries in his tests of metals below atmospheric temperatures obtained a tensile strength of 80,000 lb. per sq. in. and 6 per cent elongation for cold-drawn copper at −301° F. (−185° C.). Tensile strength and elongation of both cold-drawn and annealed copper are increased at temperatures below atmospheric. Doernickel and Trockels (Figs. 19 and 20) show the crushing strength to decrease gradually with temperature. Modulus of elasticity, according to Iokibe and Sakai, decreases according to a parabolic law.

COPPER-TIN BRONZES

The influence of temperature upon the properties of copper-tin bronzes (Fig. 5), according to Bregowsky and Spring(4), becomes most marked between 400 and 600° F. (205 and 315° C.), all of the properties except the elastic limit decreasing very rapidly within that range of temperature. At temperatures below 300 to 350° F. (150 to 175° C.) no appreciable difference in tensile strength is found for the bronzes carrying 12 per cent of tin. At all higher temperatures the 12-per-cent bronze is superior in strength to the bronze of a lower tin content. The influence of the additional tin is also shown in the effect on elongation and reduction of area at temperatures above 750° F. (400° C.). Variations in properties at elevated temperatures seemingly are dependent upon the presence of the delta constituent, the final

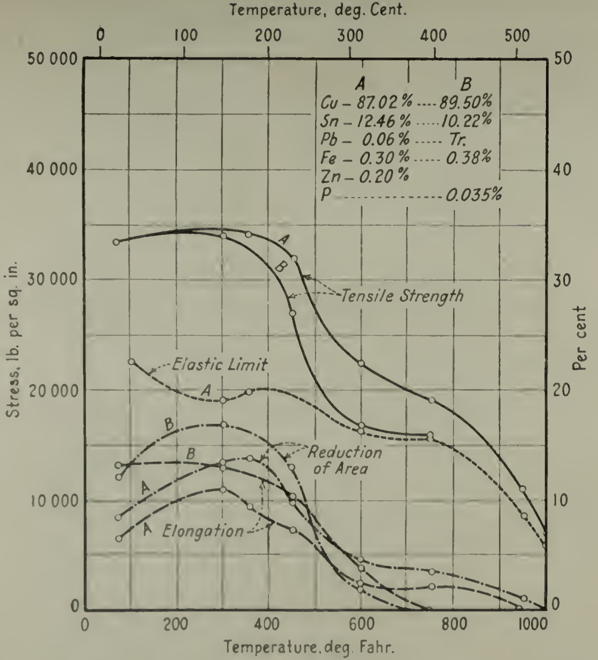

FIG. 5.—Effect of Temperature on Tensile Properties of Copper-Tin Bronze, According to Bregowsky and Spring(83).

Chemical Composition as Indicated.

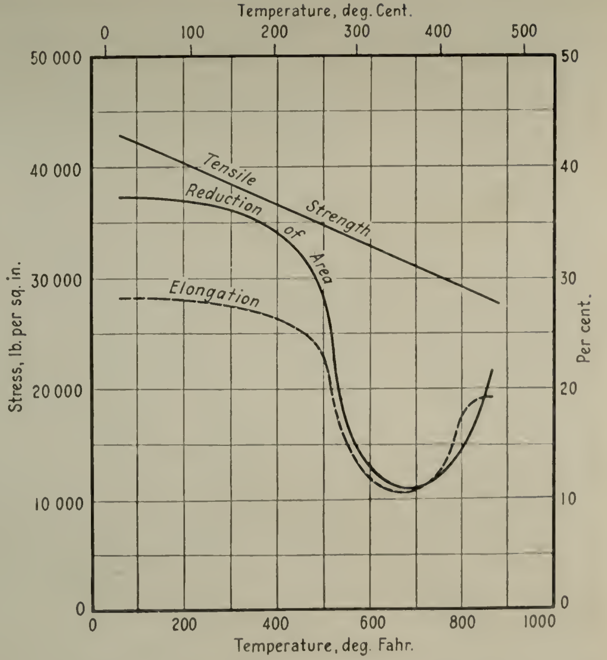

FIG. 6.—Effect of Temperature on Tensile Properties of Copper Tin Bronze, According to Huntington(85).

Chemical Composition, per cent: Cu, 97.673; Sn, 2.408; Pb, 0.024.

decrease in elongation and tensile strength coming at the temperatures corresponding to the absorption of this constituent. In view of the much higher elastic limit values obtained by Bregowsky and Spring on gun-metal bronzes than have been obtained by other investigators, the elastic limit values given in Fig. 5 may be higher than further investigation will prove to be the case.

Low-tin bronze (Fig. 6), according to Huntington(85), shows a gradual decrease in strength with increasing temperature. Elongation and reduction of area decrease rapidly at 500° F. (260° C.), reaching a minimum at 700° F. (370° C.). The results obtained by Huntington are very similar to the results obtained in 1893 by Rudeloff(20,64) with copper carrying 1.86 per cent tin. This copper-tin alloy shows a tensile strength superior to that of copper at all temperatures up to 900° F. (480° C.).

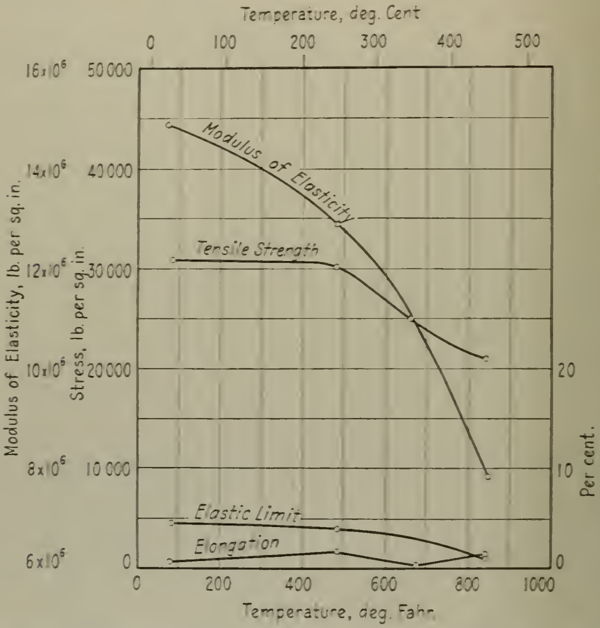

FIG. 7.—Effect of Temperature on Tensile Properties of Phosphor Bronze, According to Lea(142).

Chemical Composition, per cent: Cu, 85.38; Sn, 12.55; Zn, 1.01; P, 0.24; Fe, 0.02; Pb, 0.61; Ni, 0.11.

PHOSPHOR BRONZE

Phosphor bronze (Fig. 7) retains its tensile strength undiminished up to temperatures of 450 to 500° F. (230 to 260° C.). Above 500° F. (260° C.) the strength and elastic properties decrease rapidly. According to Lea(142), the elastic limit becomes zero and the tensile strength decreases to less than 5000 lb. per sq. in. above 900° F. (480° C.).

GUN METAL

Tensile properties of gun metal, according to Lea(141,142) (Fig. 8), undergo no appreciable change up to 450 to 500° F. (230 to 260° C.). Above 500° F. (260° C.) the tensile strength and elongation decrease very rapidly. The elastic limit decreases more slowly but reaches a value of less than 4000 lb. per sq. in. at 850° F. (450° C.). Hardness decreases slowly with increase in temperature. The tensile properties of gun metal show a slight superiority over phosphor bronze for temperatures up to 450 to 500° F. (230 to 260° C.).

Bregowsky and Spring(83), in an earlier investigation, obtained very similar results for U. S. Navy Gun Bronze, though slightly lower values are given for tensile strength and for elongation than are obtained by Lea. Values for permanent set differ very widely from those obtained by Lea. The initial value at normal temperatures is given as 25,100 lb. per sq. in. as opposed to 7150 lb. per sq. in. by Lea. At 750° F. (400° C.) a value of 17,500 lb. per sq. in. is given as opposed to less than 5000 lb. per sq. in. by Lea. This difference indicates the necessity for a careful check.

Influence of 0.5 per cent of lead has been considered by Dewrance(98). Gun metal without lead (Fig. 9) undergoes no decrease in its tensile properties up to 350° F. (175° C.). Above that temperature tensile strength and elongation decrease rapidly up to 400° F. (205° C.), remaining constant up to 600° F. (315° C.), and again decreasing. With 0.5 per cent of lead present, the tensile strength and elongation remain undiminished up to a temperature of 550° F. (290° C.). Above that temperature tensile strength and elongation decrease rapidly. The retention of the tensile strength at higher temperatures with the second alloy is attributed by Dewrance to the presence of the lead. As neither Bregowsky and Spring nor Lea reported tests at 550° F. (290° C.), their results cannot be used directly to confirm or deny the results obtained by Dewrance, although Lea used an alloy with 0.12 per cent of lead and Bregowsky and Spring an alloy with 0.30 per cent of lead. However, the fact that Lea, using an alloy with

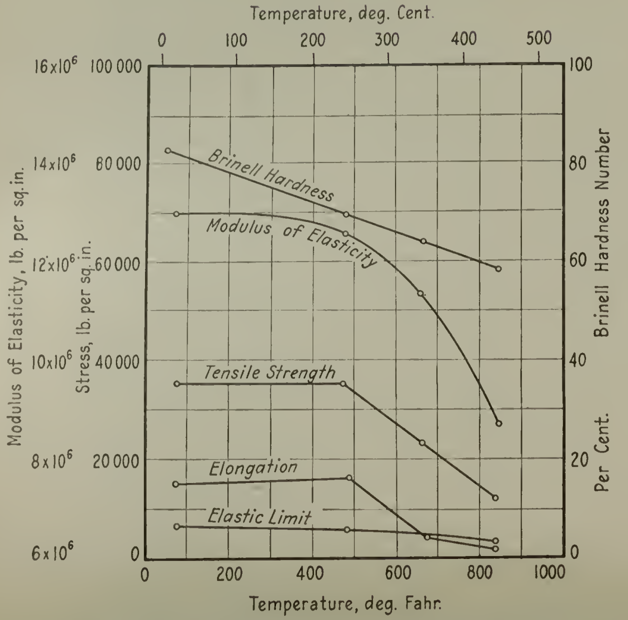

FIG. 8.—Effect of Temperature on Tensile Properties and Brinell Hardness of Gun Metal, According to Lea (141,142).

Chemical Composition, per cent: Cu, 86.52; Sn, 10.2; Zn, 3.29; Pb, 0.12.

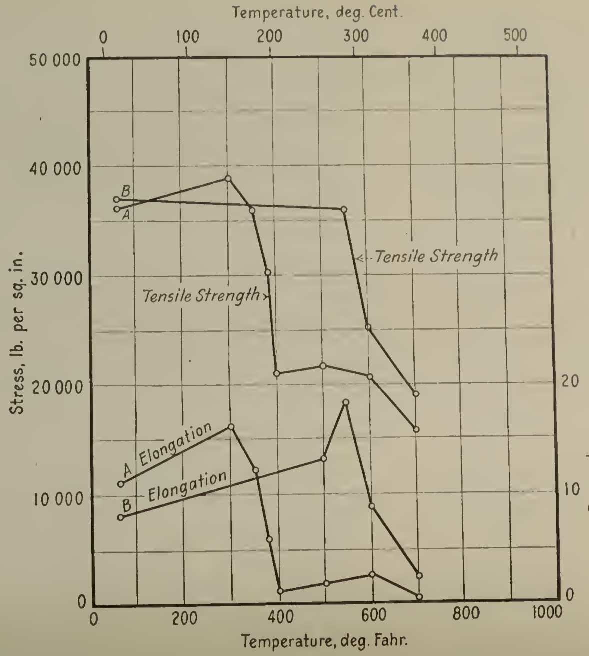

FIG. 9.—Effect of Temperature on Tensile Properties of Gun Metal, According to Dewrance (98).

Chemical Composition, per cent: A. Cu, 88; Sn, 10; Zn, 2. B. Cu, 87.5; Sn, 10; Zn, 2; Pb, 0.5.

comparatively low lead content (0.12 per cent), shows the tensile strength unchanged up to a temperature of 482° F. (250° C.) leaves the suggested superiority of the 0.5-per-cent-lead bronze somewhat in doubt. Dewrance gives no analysis of the metal actually tested, but it should be pointed out that his gun metal alloy without lead was made from copper with a purity of 99.55 per cent and carrying 0.08 per cent lead. The sharp increases in elongation noted by Dewrance were not observed by either Lea or Bregowsky and Spring.

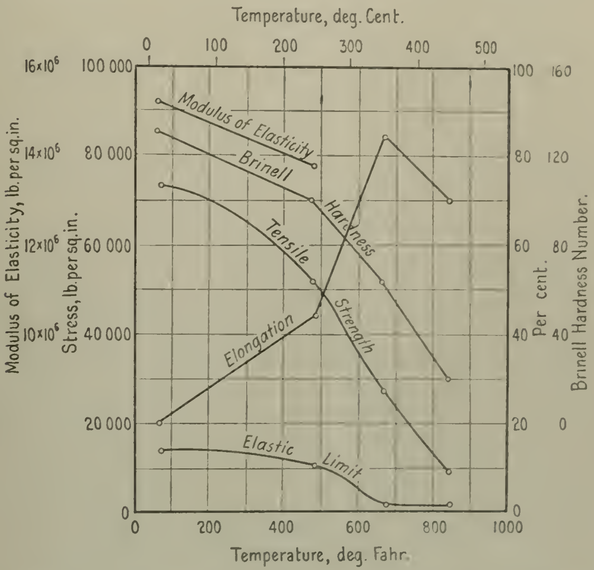

FIG. 10.—Effect of Temperature on Tensile Properties and Brinell Hardness of Cast Manganese Bronze, According to Lea(141,142).

Chemical Composition, per cent: Cu, 58.61; Zn, 36.9; Sn, 0.08; Mn, 1.88; Al, 1.01; Fe, 1.46; Pb, 0.06.

MANGANESE BRONZE

The tensile properties of cast and drawn manganese bronze (Figs. 10 and 11) change rapidly with increasing temperatures. Tensile strength decreases to 60 to 70 per cent of its original value at 500° F. (260° C.). Above that temperature the rate of decrease is more rapid. Elongation of both cast and drawn manganese bronze increases with increasing temperatures, reaching a maximum at 650 to 700° F. (345 to 370° C.), according to Lea(141,142). Brinell hardness changes with tensile strength. Elastic limit decreases slightly up to 500° F. (260° C.), then falls rapidly for cast metal. The elastic limit of drawn metal shows a continuous decrease.

Earlier results of Bregowsky and Spring (83) are in agreement with those of Lea as to tensile strength changes and elongation except for the maximum noted by Bregowsky and Spring at 500° F. (260° C.) and Lea at 650 to 700° F. (345 to 370° C.). As regards elastic limit the shape of the curve is the same for both, no appreciable drop occurring below 450° F. (230° C.). Original values, however, are decidedly different, a difference which undoubtedly reverts to the method of determining elastic limit. In either case the elastic properties of manganese bronze practically disappear between 700 and 800° F. (370 to 425° C.).

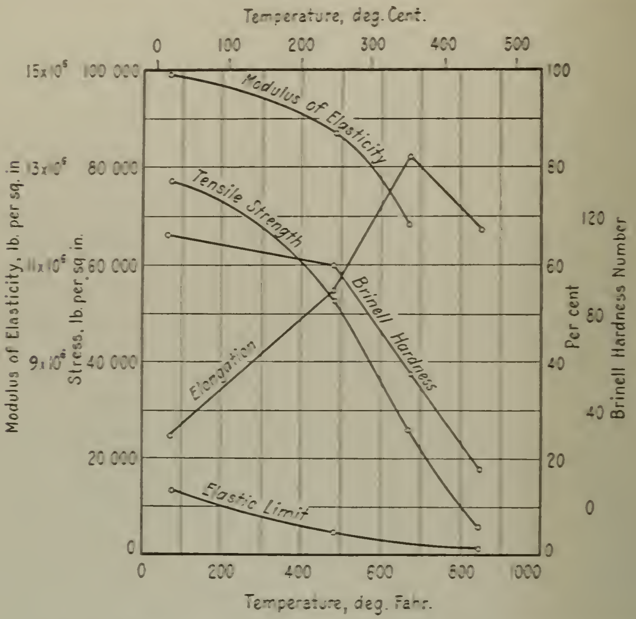

FIG. 11.—Effect of Temperature on Tensile Properties and Brinell Hardness of Drawn Manganese Bronze, According to Lea (141,142).

Chemical Composition, per cent: Cu, 56.91; Zn, 40.28; Sn, 0.75; Mn, 0.19; Fe, 0.82; Pb, 0.66; Al, 0.18; Ni, 0.21.

ALUMINUM BRONZE

Early tests by Rosenhain (57) on rolled aluminum bronze showed the superiority at all temperatures up to 800 to 900° F. (425 to 480° C.)

of the 10-per-cent aluminum bronze over the 5-per-cent bronze. Elongation of the 10-per-cent or two-constituent bronze increases up to 900° F. (480° C.), while the 5-per-cent bronze shows a continuous decrease in elongation. The influence of increasing the percentages of manganese was also tried by Rosenhain but this did not result in material improvement in the properties of the bronze.

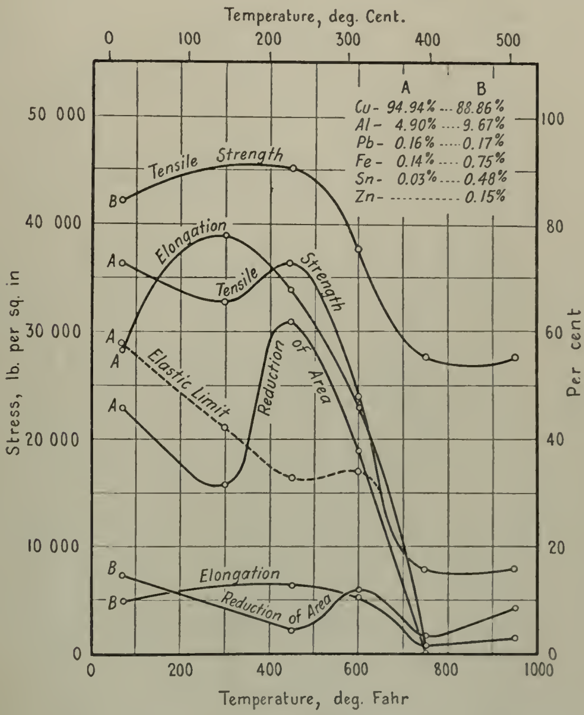

FIG. 12.—Effect of Temperature on Tensile Properties of Aluminum Bronze, According to Bregowsky and Spring(83).
Chemical Composition as Indicated.

Bregowsky and Spring(83) (Fig. 12) found the cast 10-per-cent aluminum bronze superior in tensile strength at all temperatures to the 5-per-cent bronze. No appreciable decrease in strength occurs in the 10-per-cent bronze below 600° F. (315° C.). Above that temperature and up to 900° F. (480° C.), the strength remains very nearly equal to the initial strength of the 5-per-cent bronze.

Edwards and Herbert(151) have also carried out dynamic tests, referred to under brasses, on copper-aluminum alloys.

BRASSES

Tensile properties of brasses at elevated temperatures have been investigated by Bengough and Hanson(96), Huntington(85) and Lea(141,142). Edwards and Herbert(151) have investigated the plasticity of brasses by means of dynamic rather than tension tests, while Doernickel and Trockels(149) have investigated the compressibility.

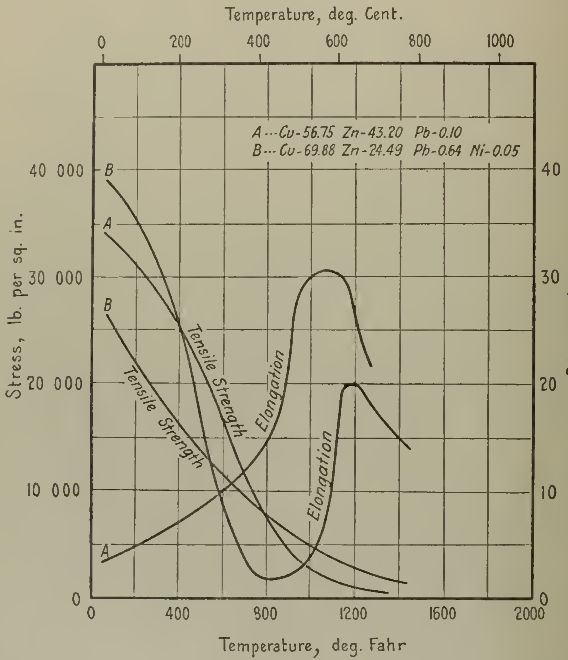

FIG. 13.—Effect of Temperature on Tensile Properties of Cast Brass, According to Bengough(82).
Chemical Composition as Indicated.

The tensile strength of cast brasses (Fig. 13) decreases rapidly with increased temperatures, falling to values of less than 5000 lb. per sq. in. at 1000° F. (540° C.), according to Bengough(82). The elongation of the 70–30 brass, single-constituent type, falls rapidly to a minimum value at 800° F. (425° C.) and again increases to a

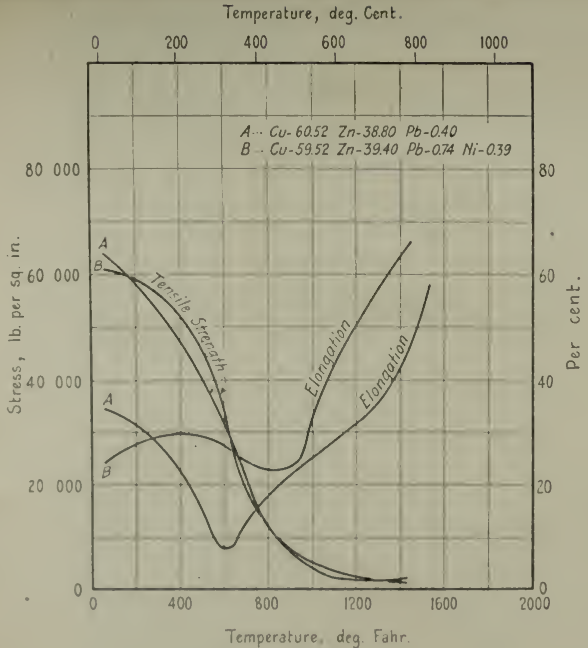

FIG. 14.—Effect of Temperature on Tensile Properties of Rolled Muntz Metal, According to Bengough **(82)**.

Chemical Composition as Indicated.

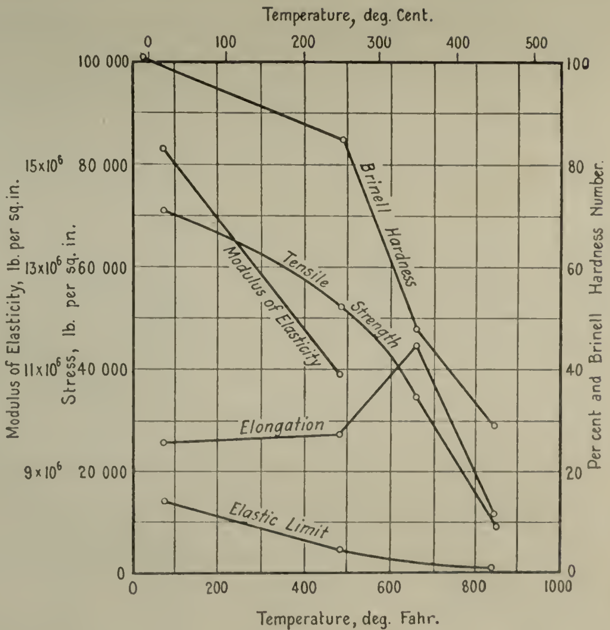

FIG. 15.—Effect of Temperature on Tensile Properties and Brinell Hardness of Modified Muntz Metal, According to Lea **(141,142)**.

Chemical Composition, per cent: Cu, 58.96; Zn, 39.77; Sn, 0.56; Pb, 0.67.

maximum at 1200° F. (650° C.). The elongation of the 60–40, or two-constituent brass, increases somewhat slowly at first, but above 800° F. (425° C.) it increases rapidly to a maximum with absorption of the alpha constituent.

The tensile properties of extruded brass vary with increasing temperatures in practically the same way as for cast brass, according to both Huntington and Bengough.

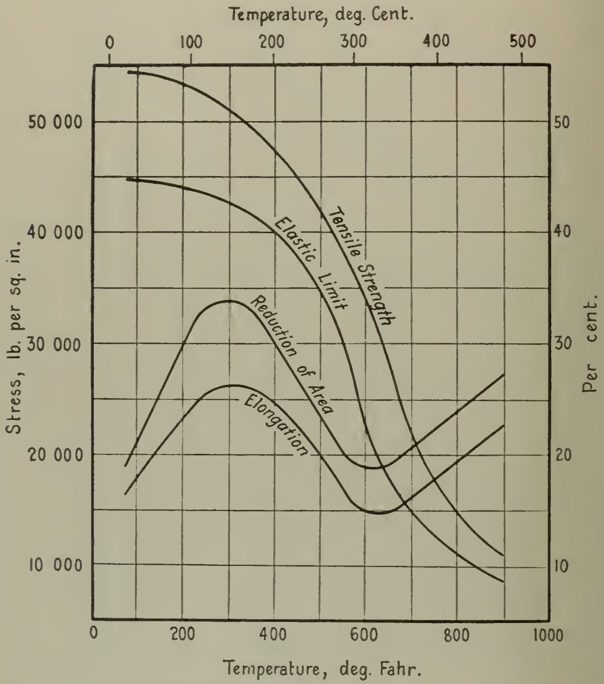

FIG. 16.—Effect of Temperature on Tensile Properties of Leaded Brass, According to Crane Co. (216).

Chemical Composition, per cent: Cu, 62.5; Zn, 35; Pb, 2.5.

Rolled brass of the Muntz metal type (Fig. 14) undergoes a somewhat slower change in tensile strength up to temperatures of 400 to 500° F. (205 to 260° C.). Above 500° F. (260° C.) the tensile strength of Muntz metal decreases to less than 10,000 lb. per sq. in. between 800 and 900° F. (425 to 480° C.), or slightly below, according to Lea (Fig. 15). Slight changes in composition, while apparently having little influence on tensile strength, may have a very marked effect on elongation as is shown in Fig. 14.

Rolled rod brass, 62.5 per cent copper and 2.5 per cent lead, according to the Crane Co. (Fig. 16) retains its tensile strength and elastic properties with very small changes up to a temperature of from 400 to 500° F. (205 to 260° C.). At temperatures above 500° F. (260° C.) tensile strength and elastic limit drop very rapidly. Compared to the *B* composition Muntz metal (Fig. 14) there appears to be very little difference in the properties of the two alloys.

Edwards and Herbert have investigated the plasticity of brasses at elevated temperatures, employing a dynamic test rather than the more commonly used static test. Plasticity is measured in terms of the indent made by the application of a 63-in-lb. blow. This is converted by the formula $\frac{7455}{d^3} = H$ to Brinell numbers, d being the diameter of the indent. In making the tests the samples were supported on a steel dummy and held at temperature for 15 minutes previous to the test. The time required for the blow was estimated as not exceeding 2 to 3 seconds. With this method of testing, alpha brasses show no change in plasticity up to 1100° F. (600° C.). See Figs. 17 and 18. Above 1100° F. (600° C.) they become very slightly more plastic. With an alpha-beta brass—31.12 per cent zinc, 61.9 per cent copper—a slight softening occurs below 850° F. (450° C.). Above that temperature softening is rapid. Alloys *C*, *D* and *E* (Fig. 17), with less than 60 per cent copper, show a slight decrease in plasticity up to 850° F. (450° C.), followed by a very rapid increase up to 1100° F. (600° C.). Alloys of copper and zinc, in which the beta constituent is present, become much more plastic above 850° F. (450° C.). Edwards and Herbert also observed that the degree of plasticity was much greater at 1600° F. (870° C.) if the brass was cooled down to the temperature rather than heated up to the temperature. In Fig. 18 the curves are plotted to show the effect of composition for the temperatures at which the tests were made.

Compression or crushing tests have been made on brasses at elevated temperatures by Doernickel and Trockels (Figs. 19 and 20). In these tests the work required to compress cylinders 18 mm. in diameter and 36 mm. long to 50 per cent of their length was determined. With copper the decrease in work required to produce 50 per cent compression is very nearly continuous, dropping from slightly less than 1200 ft-lb. to less than 200 ft-lb. at 1400° F. (760° C.) The curve is not unlike the tensile strength curve. The brasses show a critical point or inflection above which the work required to produce

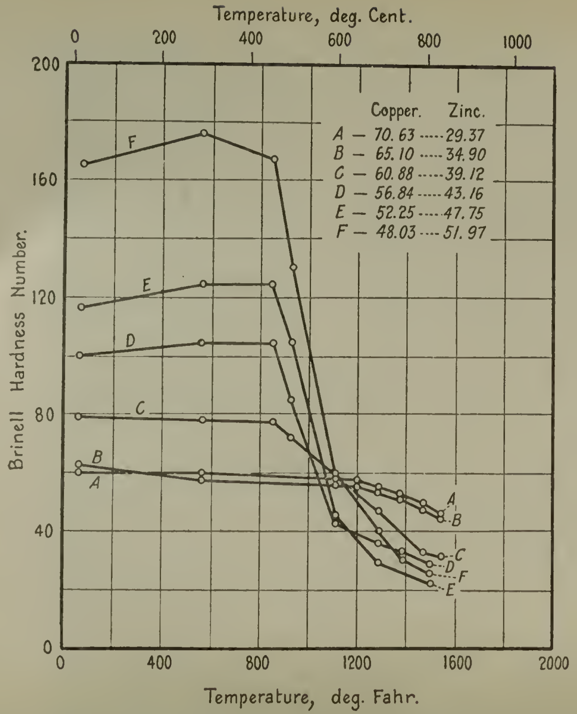

FIG. 17.—Effect of Temperature on Plasticity of Copper-Zinc Alloys, According to Edwards and Herbert(151).
Chemical Composition as Indicated.

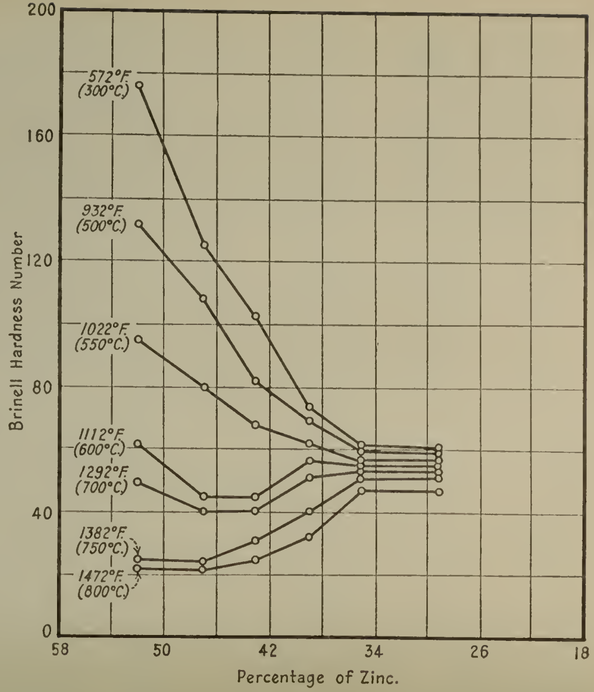

FIG. 18.—Effect of Chemical Composition on Plasticity of Copper-Zinc Alloys at Various Temperatures, According to Edwards and Herbert(151).

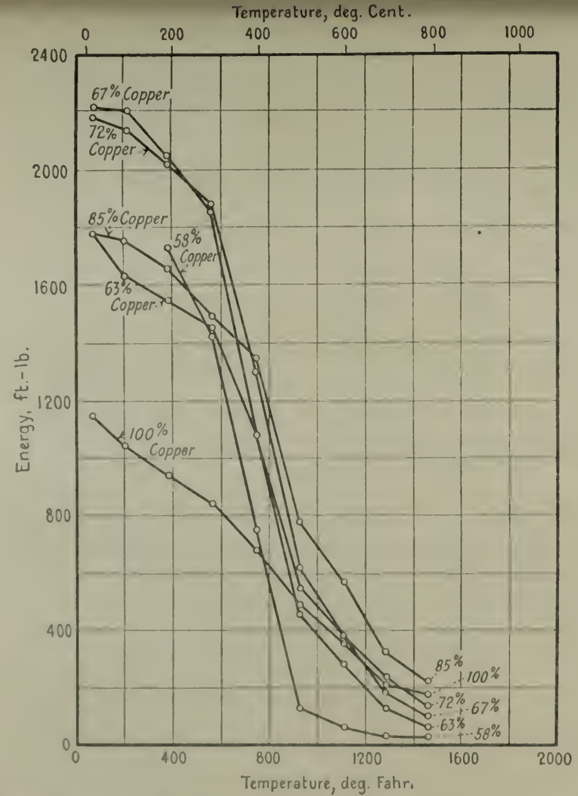

FIG. 19.—Effect of Temperature on Resistance to Compression of Copper-Zinc Alloys, According to Doernickel and Trockels (**149**). Chemical Composition as Indicated.

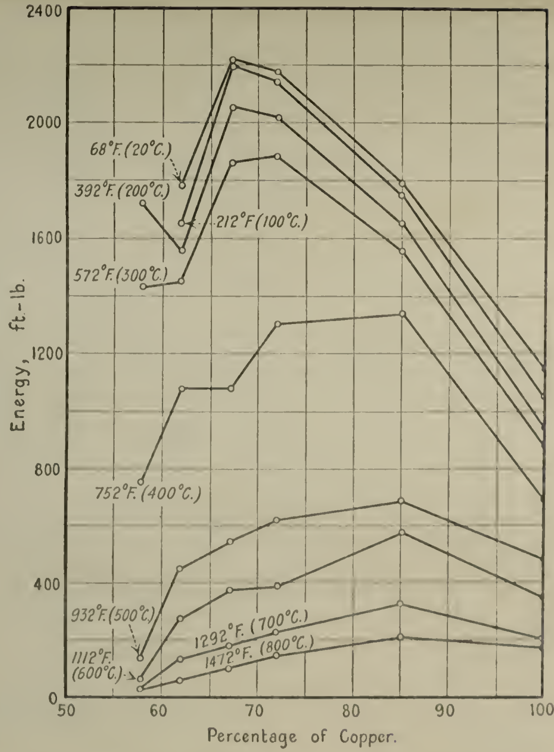

FIG. 20.—Effect of Chemical Composition on Resistance to Compression of Copper-Zinc Alloys at Various Temperatures, According to Doernickel and Trockels(**149**).

a given compression falls off rapidly. Above 932° F. (500° C.) low-zinc brasses offer the greatest resistance to crushing. Below 572° F. (300° C.) the 67 to 72-per-cent copper brasses offer the greatest resistance to crushing. Here, as with Edwards' dynamic tests, the changes due to composition are most marked at the lower temperatures.

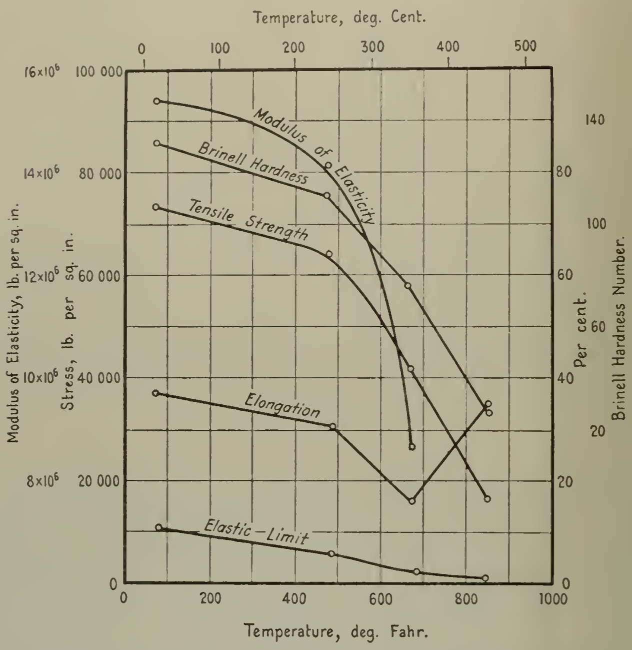

FIG. 21.—Effect of Temperature on Tensile Properties and Brinell Hardness of Delta Metal, According to Lea (141,142).

Chemical Composition, per cent: Cu, 58.27; Zn, 39.05; Fe, 0.13; Sn, 0.06; Ni, 2.2; Mn, 0.14; Pb, 0.15.

DELTA METAL

The tensile strength and elastic properties of Delta metal (Fig. 21) decrease slowly up to 500° F. (260° C.). Above that temperature the tensile strength decreases rapidly and the elastic limit approaches zero between 700 and 800° F. (370 to 425° C.). Delta metal is shown to retain its tensile strength somewhat better than Muntz metal (Fig. 15) up to 400° F. (205° C.) and is slightly superior at all temperatures up to 800° F. (425° C.). There appears to be little difference in the elastic properties of the two metals.

COPPER-NICKEL ALLOYS

Copper-nickel alloys, according to Lea(141,142), Huntington(85) and Bengough(82) (Figs. 22, 23 and 24) retain their strength very well up to temperatures of 600 to 800° F. (315 to 425° C.), depending upon the nickel content. The influence of the nickel content up to 12 per cent appears to be most marked at temperatures below 400° F. (205° C.). The elastic limit in the 2-per-cent alloys remains practically unchanged up to 600° F. (315° C.), and suggests to Lea that the copper-nickel series may offer very desirable alloys for elevated temperatures. The elastic limit has not been determined for the higher nickel contents. However, neither the 2-per-cent nor the 12-per-cent nickel alloys retains its strength to any greater extent than the 2.5-per-cent tin bronze (Fig. 6).

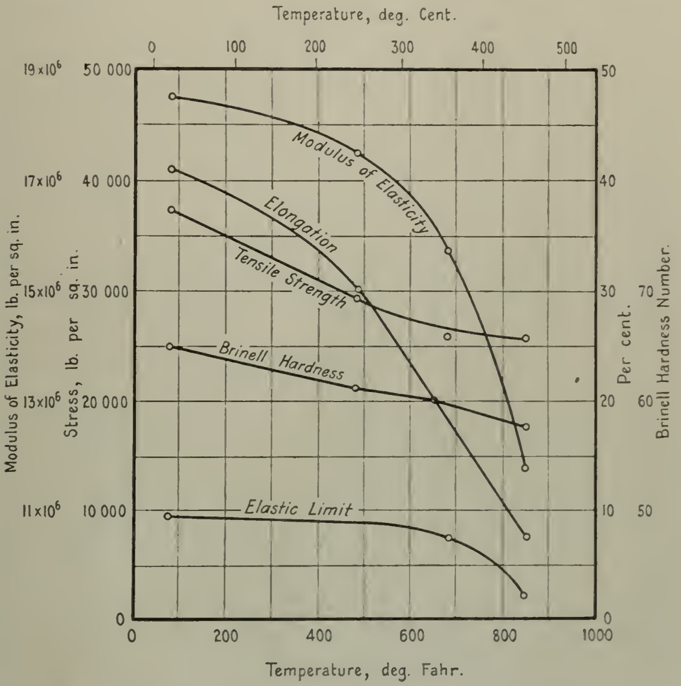

FIG. 22.—Effect of Temperature on Tensile Properties and Brinell Hardness of Copper-Nickel Alloy, According to Lea(141,142).

Chemical Composition, per cent: Cu, 97.80; Ni, 2.0; Al, 0.20.

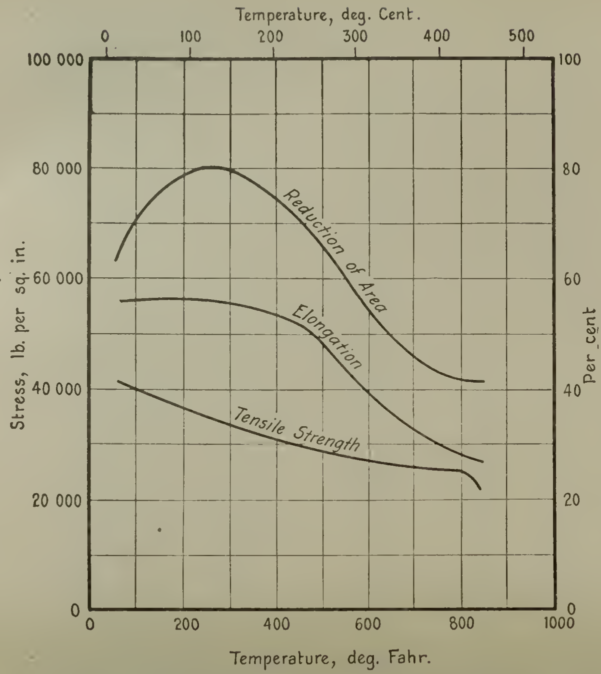

FIG. 23.—Effect of Temperature on Tensile Properties of Copper-Nickel Alloy, According to Huntington(85).

Chemical Composition, per cent: Cu, 88; Ni, 12.

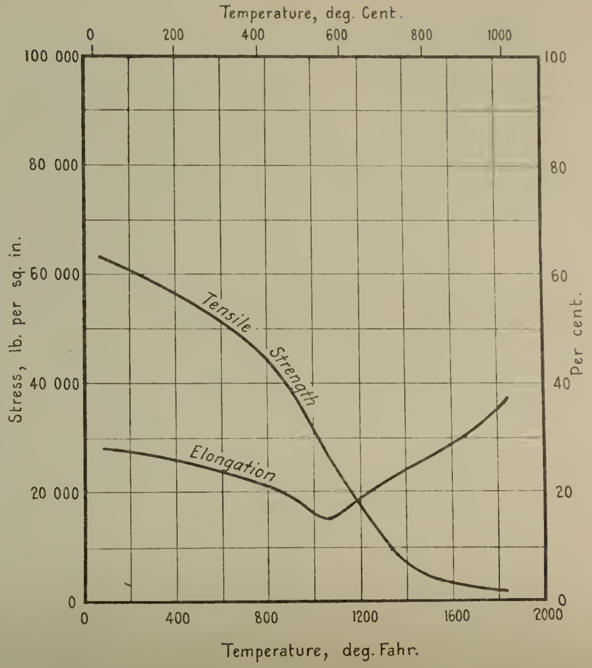

FIG. 24.—Effect of Temperature on Tensile Properties of Copper-Nickel Alloy, According to Bengough(82).

Chemical Composition, per cent: Cu, 79.99; Ni, 19.6; Fe and Mn, 0.41.

The 20-per-cent nickel alloy when cold rolled behaves very similarly to Muntz metal at the same temperatures as regards the tensile strength and elongation.

COPPER-TIN-ZINC-LEAD ALLOYS (STEAM BRONZE TYPE)

Alloys of this type usually decrease in both tensile strength and elongation between 500 and 600° F. (260 and 315° C.). The properties of the three alloys investigated by Bregowsky and Spring(83) are shown in Figs. 25, 26 and 27. The U. S. Navy bronze shows slightly better tensile and elastic properties up to 500° F. (260° C.) than the other two. Between 500 and 600° F. (260 and 315° C.) the tensile strength of each of the alloys has decreased to about one-half of the initial value. Above 600° F. (315° C.) the tensile strength decreases more slowly. The elongation approaches zero.

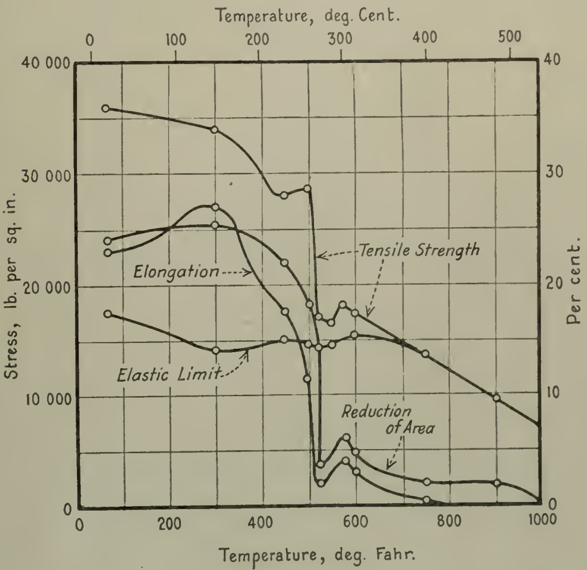

FIG. 25.—Effect of Temperature on Tensile Properties of U. S. Navy Bronze M, According to Bregowsky and Spring(83).

Chemical Composition, per cent: Cu, 86.92; Sn, 7.72; Zn, 3.62; Pb, 1.22; Fe, 0.23.

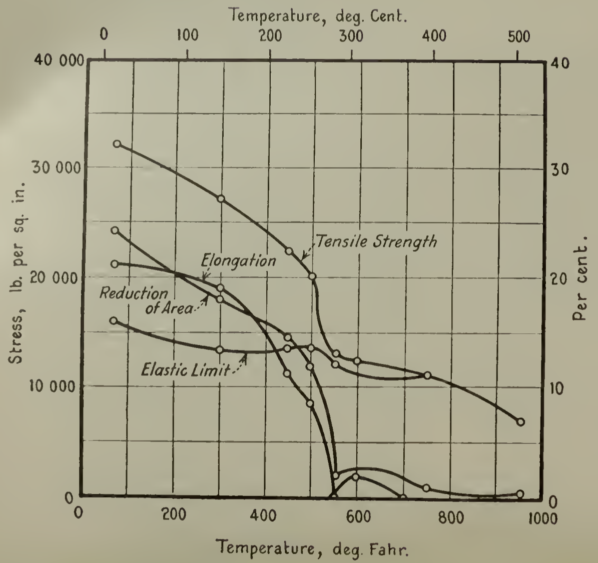

FIG. 26.—Effect of Temperature on Tensile Properties of Brass, According to Bregowsky and Spring (83).

Chemical Composition, per cent: Cu, 86.19; Sn, 5.69; Zn, 5.03; Pb, 3.02; Fe, 0.20.

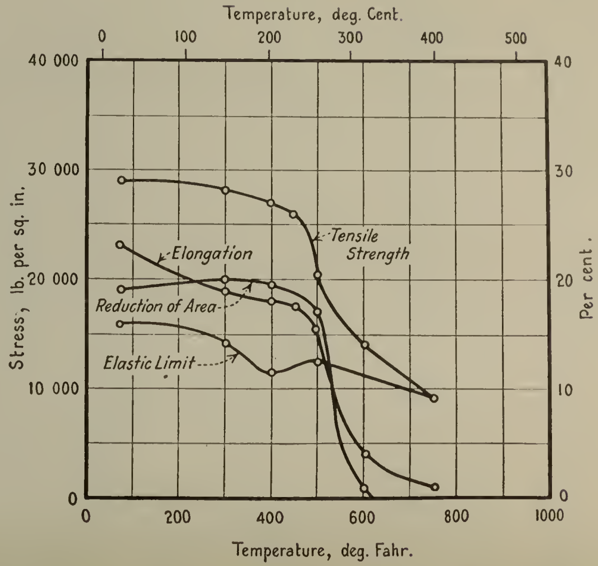

FIG. 27.—Effect of Temperature on Tensile Properties of U. S. Navy Brass S-c, According to Bregowsky and Spring (83).

Chemical Composition, per cent: Cu, 80.32; Zn, 12.80; Sn, 3.98; Pb, 2.78; Fe, 0.24.

Malcolm(212) recently presented curves for steam metal approaching the composition of the brass shown in Fig. 26. Decrease in tensile strength is slight up to 400° F. (205° C.). From 400 to 600° F. (205 to 315° C.) the decrease is rapid. From 600° F. (315° C.) up the decrease is again more gradual. The elastic limit decreases slowly from 19,800 to 8700 lb. per sq. in. at 1000° F. (540° C.). The ductility decreases somewhat more slowly.

Alloys of the leaded type invariably show loss in tensile strength and decrease in ducility when the melting point of the lead is approached, as indicated by the decrease in strength and ductility slightly below 600° F. (315° C.). The high tin alloy with low lead content shows a similar drop at 500° F. (260° C.).

NICKEL AND NICKEL CHROME

Results obtained by Sykes(146) (Fig. 28) on tests of nickel wire, purity 99.8 per cent, indicate that the tensile strength of nickel decreases slowly from atmospheric temperature—or in fact from below atmospheric temperatures—to temperatures approaching 750° F. (400° C.). Above this temperature the decrease is very rapid. Elongation also decreases from atmospheric temperatures to 575° F. (300° C.), but shows an increase at 750° F. (400° C.). Very similar results were obtained by del Regno(192), a rapid decrease in strength and increase in ducility being observed at approximately 750° F. (400° C.). Lea(142) (Fig. 29), using an impure nickel, shows a rapid decrease in tensile strength beginning between 750 and 850° F. (400 and 450° C.) with an increase in elongation at the same temperature. This constitutes an excellent example of the influence of impurities upon tensile properties.

The nickel-chrome alloy behaves similarly to the impure nickel, but decreases in its strength at lower temperatures (Fig. 29).

Some recent tests by Chevenard(170) and Le Chatelier(35) (Fig. 30) on nickel and nickel-chrome alloys indicate the necessity of greater consideration for the time element when determining properties of metals at elevated temperatures. The rate of elongation in millimeters per hour is shown for different alloys under constant load.

MONEL METAL

The tensile properties of cast monel metal presented by Bregowsky and Spring(83) (Fig. 31) are not in agreement with those recently presented by Malcolm(212) (Fig. 32). Bregowsky and Spring indicate little or no decrease in tensile strength up to 450° F. (230° C.); above

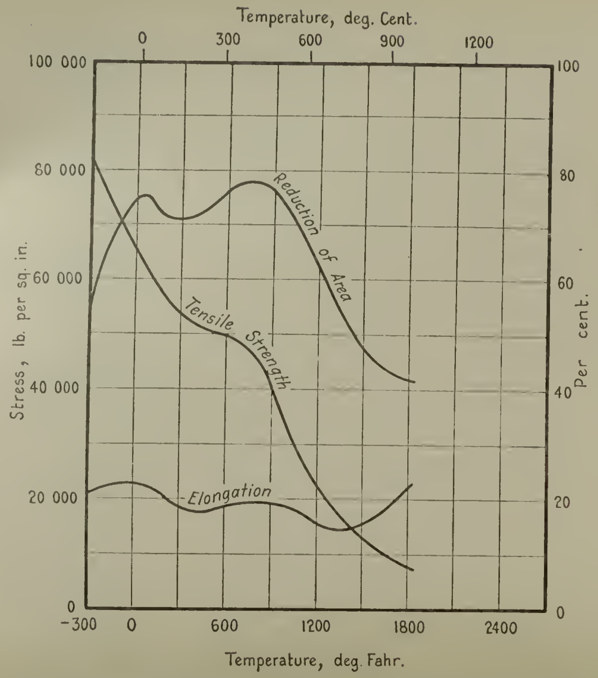

FIG. 28.—Effect of Temperature on Tensile Properties of Annealed Nickel, According to Sykes(146).

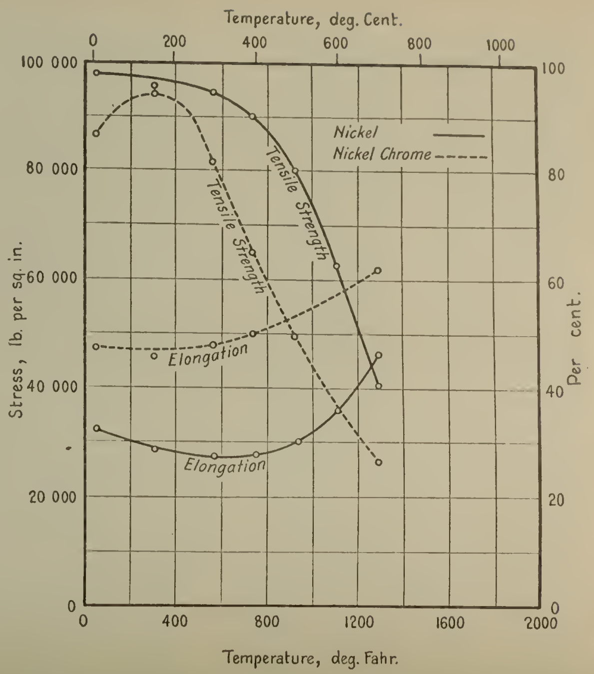

FIG. 29.—Effect of Temperature on Tensile Properties of Nickel and Nickel-Chrome, According to Lea(142).

Chemical Composition, per cent: ***Nickel.***—Ni, 95.53; Impurities, 4.47.
Nickel-Chrome.—Ni, 59.8; Cr, 12.1; C, 0.4; Mn, 2.9; Fe, 23.7.

that temperature the tensile strength decreases rapidly to 600° F. (315° C.), and then increases slightly to 800° F. (425° C.), above which temperature the fall is rapid. Malcolm indicates the tensile strength as decreasing from atmospheric temperatures up to 400° F. (205° C.),

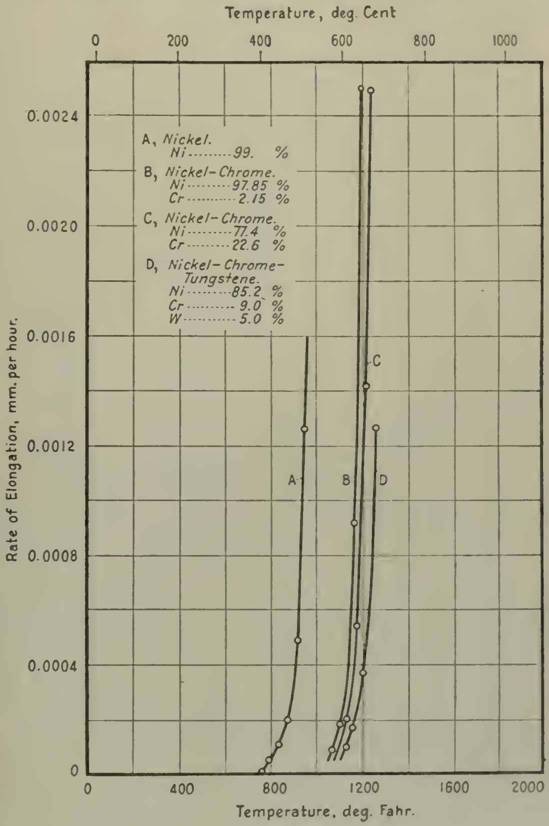

FIG. 30.—Effect of Temperature on Elongation of Nickel Alloys Under a Constant Load of 14,223 lb. per sq. in., According to Chevenard(170) and Le Chatelier(35). Chemical Composition as Indicated.

above which the tensile strength decreases very slowly. Both show the elastic limit to decrease but slightly up to 900° F. (480° C.), although the decrease is more marked according to Bregowsky and Spring. Malcolm also disagrees with Bregowsky and Spring in regard to the form of the ductility curves. Bregowsky and Spring show a maximum at 400° F. (205° C.) while Malcolm shows a minimum. Bregowsky and Spring show a reduction in ductility above 400° F. (205° C.), while Malcolm shows an increase. Malcolm's curves follow more closely the changes observed by Lea and the Allis-Chalmers Co. for worked monel metal.

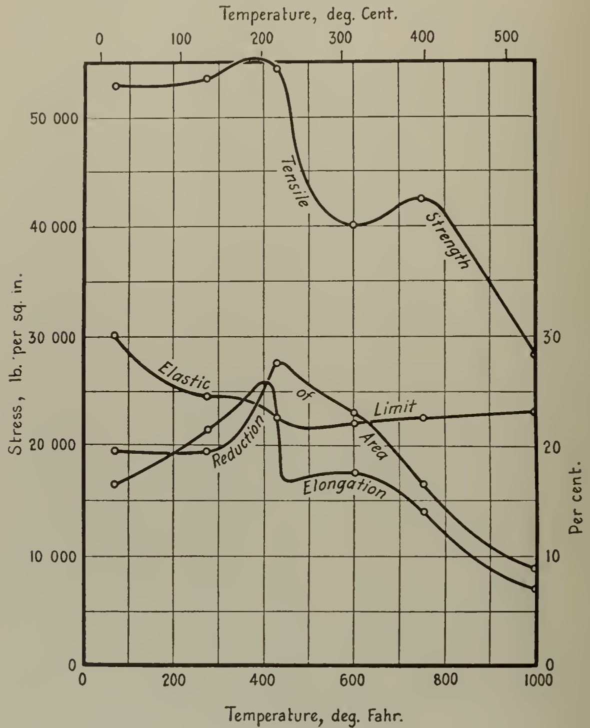

FIG. 31.—Effect of Temperature on Tensile Properties of Cast Monel Metal, According to Bregowsky and Spring (83).

Chemical Composition, per cent: Cu, 27.11; Ni, 64.79; Sn, 0.08; Pb, 0.13; Fe, 5.46; Mn, 2.33; C, 0.32.

The form of curve obtained by Bregowsky and Spring, and by Lea (142) (Fig. 33) for worked monel metal is very much the same, though there exists some doubt as to where the final drop in strength begins. All show the strength as decreasing from atmospheric temperature to 300 or 400° F. (150 or 205° C.). At

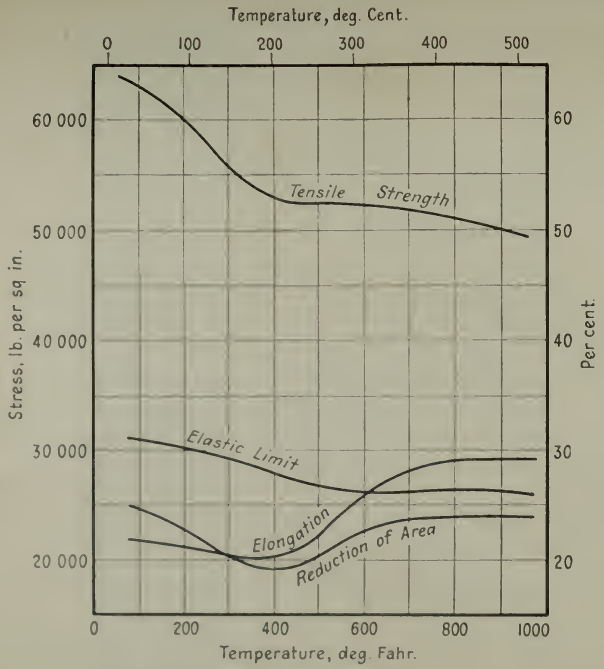

FIG. 32.—Effect of Temperature on Tensile Properties of Cast Monel Metal, According to Malcolm(212).

Chemical Composition, per cent: Cu, 29.48; Mn, 0.98; Ni, 66.63; C, 0.15; Fe, 2.36; Si, 0.40.

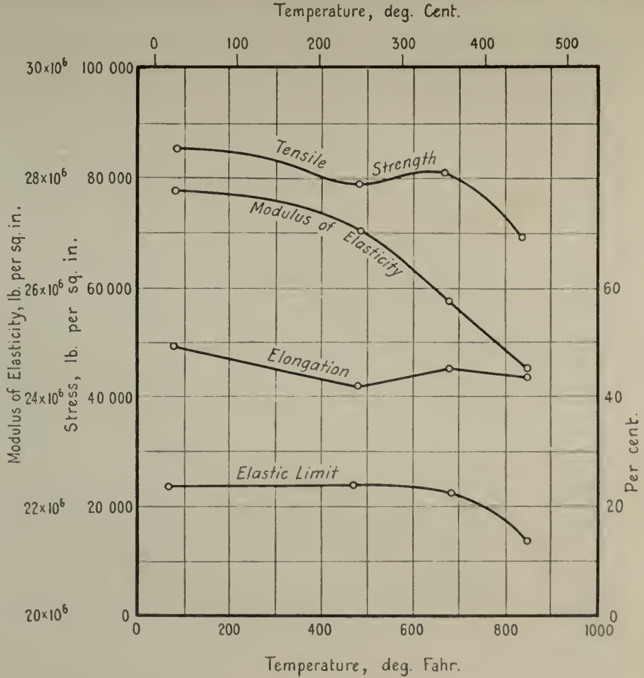

FIG. 33.—Effect of Temperature on Tensile Properties of Monel Metal, According to Lea(142).

Chemical Composition, per cent: Cu, 29.96; Ni, 66.31; Mn, 1.13; Fe, 2.24.

temperatures above 400° F. (205° C.) the tensile strength remains unchanged up to 500 to 600° F. (260 to 315° C.), up to 650 to 700° F. (345 to 370° C.) or up to 800 to 850° F. (425 to 450° C.), depending upon the investigator. According to Lea, the final and more rapid decrease in tensile strength begins between 650 and 700° F. (345 and 370° C.). The elastic limit undergoes a very marked decrease from 70 to 300° F. (21 to 150° C.) and from 600 to 800° F. (315 to 425° C.), according to Bregowsky and Spring, while Lea shows practically no

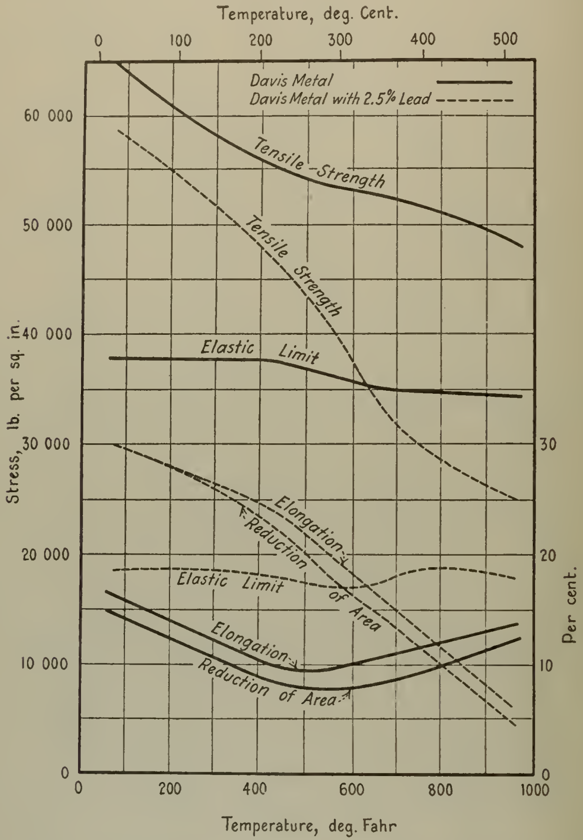

FIG. 34.—Effect of Temperature on Tensile Properties of Davis Metal, According to Malcolm(212).

Chemical Composition, per cent: Ni, 30; Cu, 65; Mn, 1; Fe, 3; remainder, C+Si.

decrease up to 700° F. (370° C.). Initial values obtained by Lea are relatively much lower than are those obtained by Bregowsky and Spring, and in fact are appreciably lower than those usually reported for monel metal.

The work of both Malcolm and Lea indicates that monel metal retains its elasticity but with relatively small decreases up to 600 to 700° F. (315 to 370° C.).

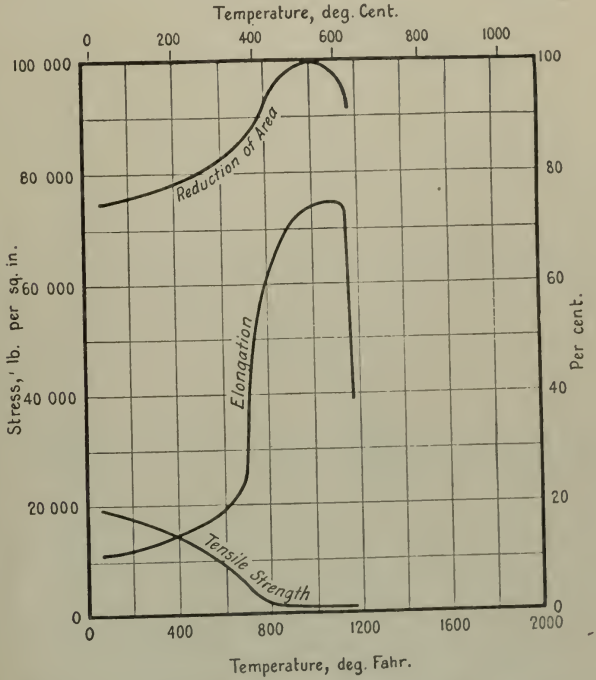

FIG. 35.—Effect of Temperature on Tensile Properties of Aluminum, According to Bengough(82)

Chemical Composition, per cent: Al, 99.56; Fe, 0.22; Si, 0.22.

DAVIS METAL

Davis Metal (Fig. 34), a copper-nickel alloy made up approximately of 30 per cent nickel, 65 per cent copper, 1 per cent manganese, 3 per cent iron, and the balance slicon and carbon, the properties of which have been very recently presented by Malcolm(212), not only retains its tensile strength at high temperatures but shows an elastic limit superior at all temperatures to monel metal. The substitution

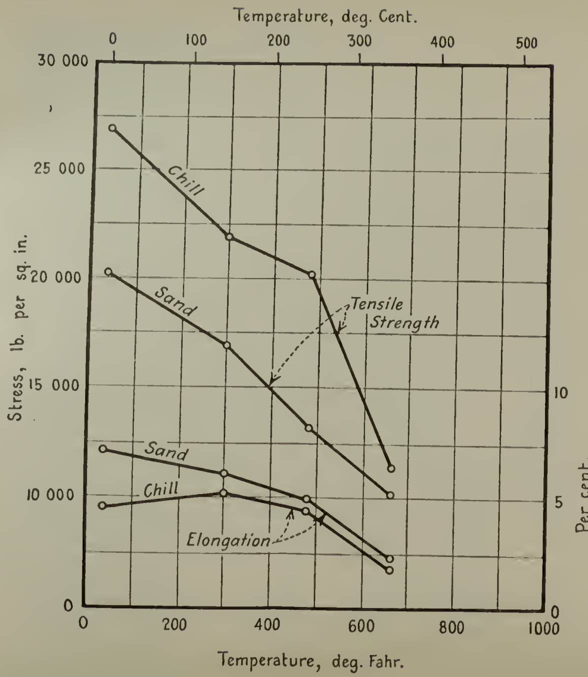

FIG. 36.—Effect of Temperature on Tensile Properties of Copper Aluminum Alloy, Chill and Sand Castings, According to Lea (187).

Chemical Composition, per cent: Al, 90; Cu, 10.

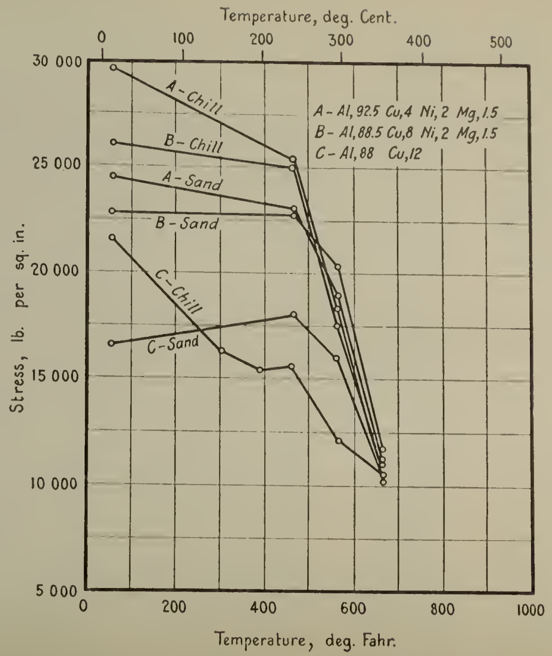

FIG. 37.—Effect of Temperature on Tensile Properties of Aluminum Alloys, Chill and Sand Castings, Eleventh Report to British Alloys Research Committee.

Chemical Composition as Indicated.

of 2.5 per cent lead (Fig. 34) decreases the strength more rapidly and cuts the elastic limit in half. The elongation and the reduction of area decrease continually with increasing temperatures.

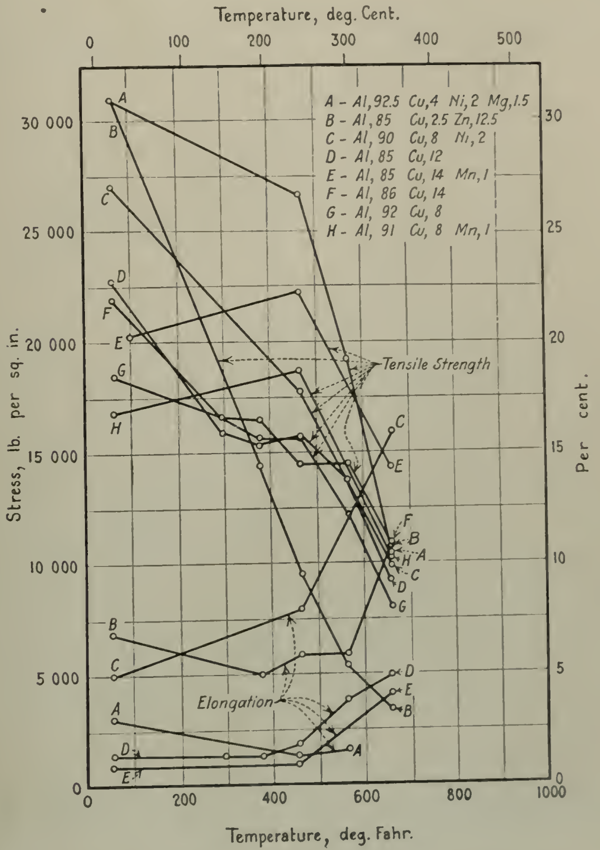

FIG. 38.—Effect of Temperature on Tensile Properties of Aluminum Alloys, Chill Castings, Eleventh Report to British Alloys Research Committee.

Chemical Composition as Indicated.

ALUMINUM AND ALUMINUM ALLOYS

The tensile strength of aluminum (Fig. 35) decreases continuously to less than 2000 lb. per sq. in. at approximately 800° F. (427° C.), while the elongation increases slowly up to 700° F. (370° C.) and then suddenly goes to a maximum between 1000 and 1100° F. (540 and 600° C.), according to Bengough(82). A very striking similarity is to be noted between the behavior of aluminum and cold-rolled copper (Fig. 3).

A large amount of data relative to the behavior of aluminum alloys at elevated temperatures has been presented in the Eleventh Report to the Alloys Research Committee(161), also in the various reports of the British Light Alloys Sub-Committee, Advisory Committee for Aeronautics. Hardness tests showed that at all temperatures from 70 to 750° F. (21 to 400° C.) the alloys containing copper were harder than those free from copper. Zinc-aluminum alloys lose their hardness very rapidly, and zinc in copper-aluminum alloys causes them to become softer at higher temperatures. Manganese

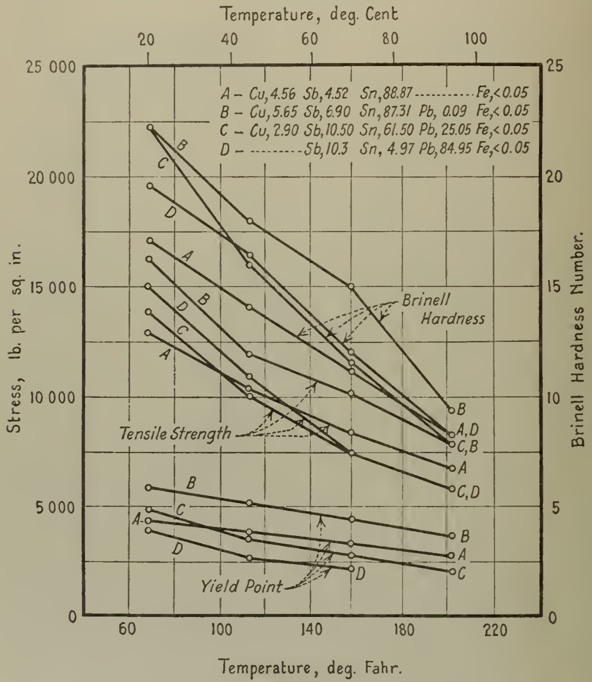

FIG. 39.—Effect of Temperature on Tensile Properties and Brinell Hardness of White Metal Bearing Alloys, According to Freeman and Woodward(152). Chemical Composition as Indicated.

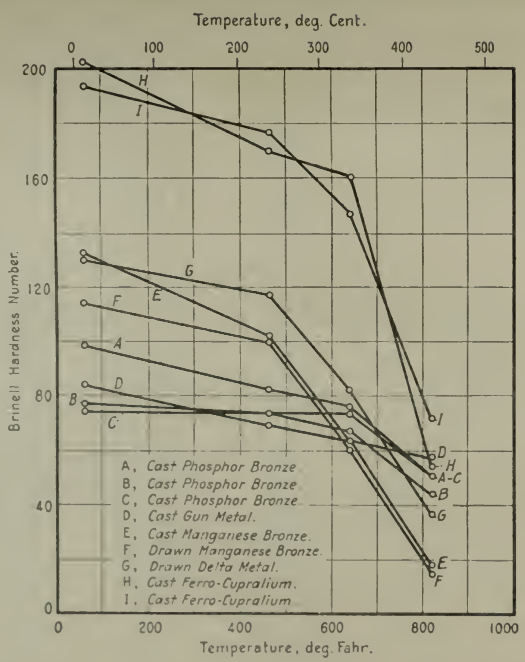

FIG. 40.—Effect of Temperature on Brinell Hardness of Copper Alloys, According to Lea(141).

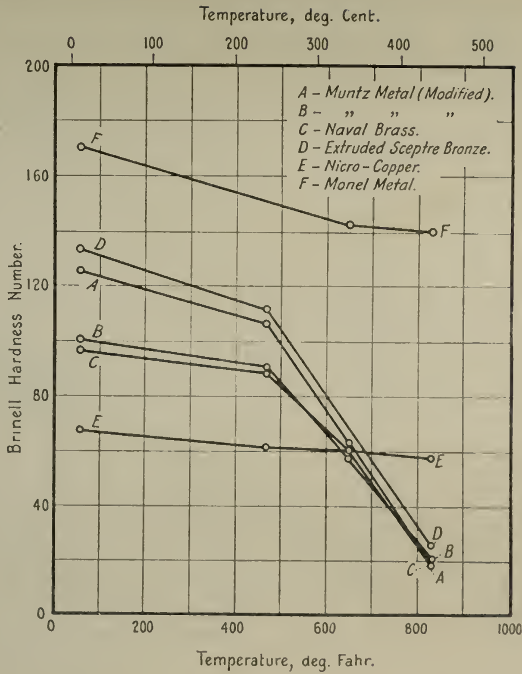

FIG. 41.—Effect of Temperature on Brinell Hardness of Copper Alloys, According to Lea(141).

and iron have the opposite effect. Tension tests on three typical aluminum alloys at low temperatures, −112° F. (−80° C.), showed no decrease in tensile properties. Impact properties of the copper-manganese-aluminum type show no change up to 480° F. (250° C.). Zinc-copper or zinc-copper-tin alloys showed a marked reduction. Duralumin decreases in resistance to impact above 150° F. (65° C.). In Figs. 36, 37 and 38 are given curves for aluminum alloys at elevated

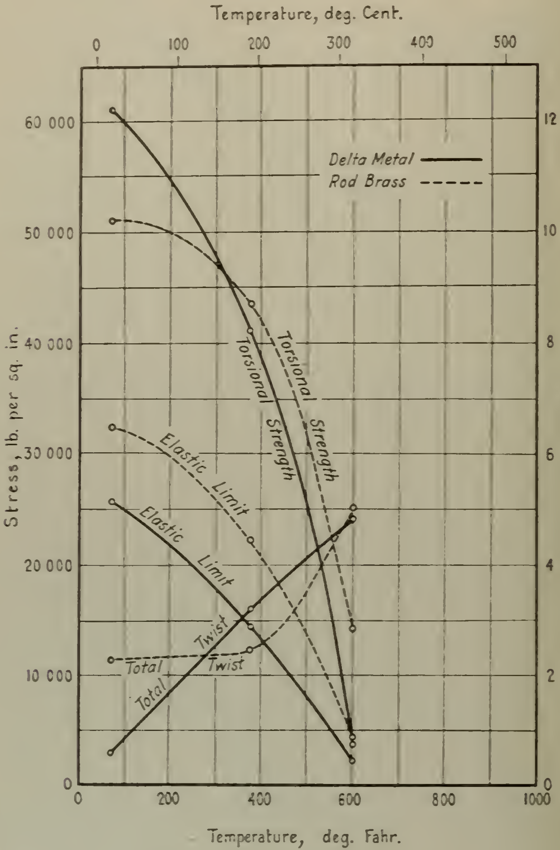

FIG. 42.—Effect of Temperature on Torsional Properties of Rod Brass and Delta Metal, According to Bregowsky and Spring (83).

Chemical Composition, per cent: *Rod Brass.*—Cu, 61.08; Zn, 35.72; Pb, 2.34; Fe, 0.42; Sn, 0.18.
Delta Metal.—Cu, 56.56; Zn, 39.36; Fe, 2.40; Sn, 0.76; Pb, 0.56; P, 0.004.

temperatures. Because of the large number of alloys which have been investigated, no attempt is made to present more than a few which may be considered typical.

Lea(187) in summing up the influence of temperature upon the properties of aluminum alloys points out that while the properties of most of the aluminum alloys change at temperatures above 480° F. (250° C.), there is little danger of aluminum pistons failing at temperatures below 650° F. (345° C.).

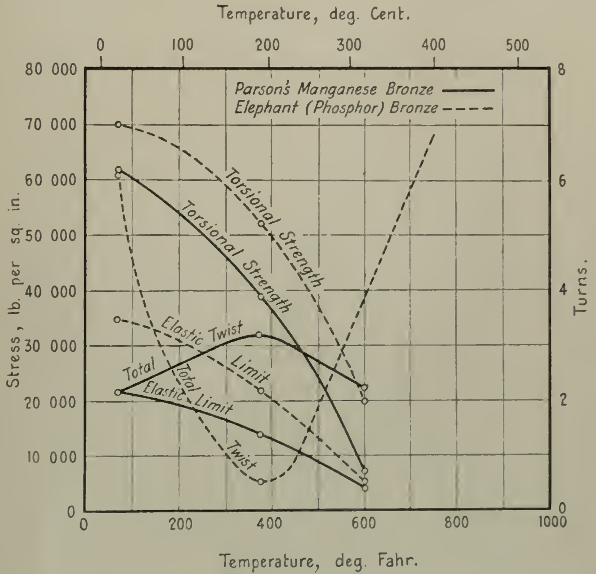

FIG. 43.—Effect of Temperature on Torsional Properties of Parson's Manganese Bronze and Elephant (Phosphor) Bronze, According to Bregowsky and Spring(83).

Chemical Composition, per cent: *Parson's Manganese Bronze.*—Cu, 59.58; Zn, 38.08; Fe, 1.22; Sn, 0.64; Al, 0.34.

Elephant (Phosphor) Bronze.—Cu, 95.52; Sn, 3.87; P, 0.307; Fe, 0.16.

BEARING METALS

Very little work relative to bearing alloys has been done at elevated temperatures. Freeman and Woodward(152), of the U. S. Bureau of Standards, have made compression and hardness tests on white metal bearing alloys (Fig. 39). The tensile strength, yield point, and Brinell hardness decrease with increasing temperatures. Alloy *B* is superior to the other alloys in the retention of strength and elasticity.

HARDNESS OF ALLOYS

Variations in hardness with increasing temperatures have been determined by Lea(141) and others. Typical hardness curves for a number of alloys according to Lea are shown in Figs. 40 and 41. Lea states that the hardness curve follows the tensile curve.

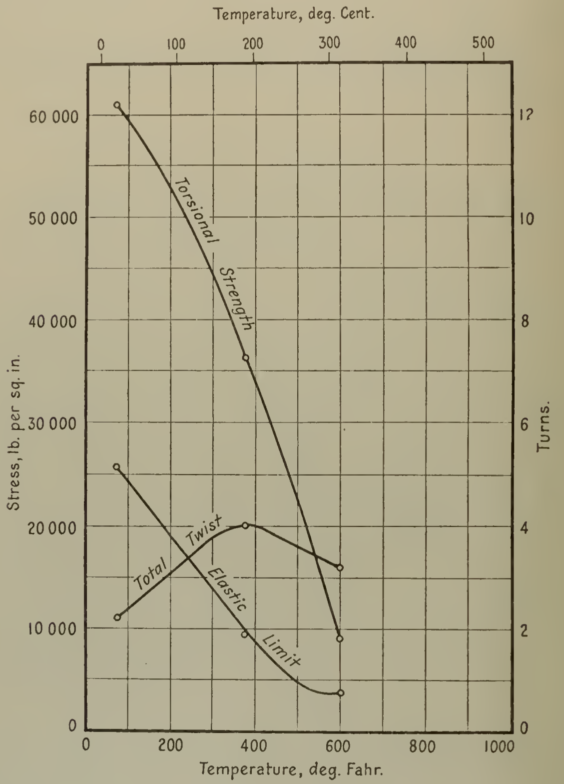

FIG. 44.—Effect of Temperature on Torsional Properties of Tobin Bronze, According to Bregowsky and Spring(83).

Chemical Composition, per cent: Cu, 59.86; Zn, 38.94; Sn, 0.80; Fe, 0.46; P, 0.0015.

TORSION TESTS

Torsion tests on five non-ferrous alloys were reported by Bregowsky and Spring(83) in 1912. The values obtained are shown in

Figs. 42, 43 and 44. Torsional strength, elastic limit and number of turns are given. No additional tests of this type have been reported in the intervening period.

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(216)	1924	"An Investigation into the Effect of High Temperatures upon Metals," *Circular No. 163*, Crane Co. (Chicago).

INDEX TO BIBLIOGRAPHY[1]

INDEX TO BIBLIOGRAPHY COVERING FERROUS METALS

(Includes the majority of references subsequent to 1914 and a few earlier ones.)

Type of Test	Cast Iron	Malleable Iron and Semi-steel	Cast Steels	Mechanically Worked Metals		High Alloy Content Steels and Heat Resisting Alloys
				Wrought Iron and Carbon Steels	Ordinary Structural Alloy Steels	
Tension	119 183 147 197	131 216 147	147 212 150 216	109 147 164 196 113 150 172 204 116 153 177 206 119 155 178 208 125 156 179 214 127 158 181 132 160 187 144 162 190	123 162 196 133 164 204 153 170 208 157 172 210 158 174 212 160 179	109 158 172 123 160 180 127 162 196 133 163 204 148 164 216 157 170
Torsion				214 216		216
Hardness	198			53 63 156 62 71 198	63 71 133	71 123 133
Crushing	71		71	71	71	71
Impact				113 156 200 125 160 201	160 201 200 210	123 160 201
"Flow" Tests				172	124 172	170 172
Expansion	193	131		117 193	117 143 193	117 193 126 194
Intercrystallin Deterioration	111 185 145			118 137 167 127 138	137 172	172
Oxidation (includes mainly scaling tests)	182			123 182 172 205	123 133 172	115 133 205 123 172
Special References or Descriptive Reports	145			105 129 154 167 110 134 155 199 114 137 159	110 140 199 137 167	126 136 135 154

INDEX TO BIBLIOGRAPHY COVERING NON-FERROUS METALS

(Includes the majority of references subsequent to 1910 and a few earlier ones.)

Type of Test	Copper	Brasses	Bronzes	Cupro-nickel	Nickel and Nickel Alloys	Aluminum and Aluminum Alloys	Bearing Metals	Miscellaneous
Tension	64 127 79 141 82 142 85 154 96 171 102 187 107	64 141 82 142 83 171 85 187 102 216 107	57 141 64 142 73 171 79 187 83 190 85 212 98 216 122	79 141 82 142 85 171	106 190 142 192 146 212 154 216 170	82 154 85 161 146 187		100 146 127 154
Torsion	108	108	108	108	108			108 154
Hardness	112 151 120 175	120 175 141	120 175 141	120 151 141 175	112 141	112 151 120 161 141 175	152	112 151 120 175
Crushing	149	149						
Impact	120 175	120 175	57 73	120 175		120 175 161		
"Flow" Test	151			151		151		151
Miscellaneous			176					

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[1] The numbers given are those of the papers in the Bibliography and include any discussions of the original reports

DISCUSSION

Mr. Wilhelm.

MR. R. B. WILHELM[1] (*presented in written form*).—This discussion deals with the tensile properties of medium-carbon steel at temperatures between 20 and 500° C. A description of the apparatus used for these tests is given, together with certain numerical data obtained. The discussion describes only the beginning of an investigation planned by the Westinghouse Electric and Manufacturing Co., the main points of which will be to investigate the properties of certain materials under prescribed conditions. The effect of time at high temperatures is also included in the program. From the results of the investigations so far published on this subject, the behavior of the material either under normal test conditions or under a long-time effect are separately considered. It is felt that some valuable results from both methods of testing can be obtained if these tests are made on the same materials. Such is the object in view, of which the results given are preliminary.

In the normal tension test, special care was taken to determine the modulus of elasticity and proportional limit. From the modulus of elasticity given in the paper, it is possible to obtain some data on the value of the modulus of rigidity at different temperatures by considering the values for Poisson's ratio for different temperatures as found and published by H. Carrington.[2]

Since it is our opinion that a difference in one of the constituent elements of the steel may materially affect the properties at high temperatures, the complete chemical analysis is given of the material tested. This may possibly help to clear up the seemingly contradictory results found by different investigators. We note, for instance, that for carbon steels of similar carbon content the values of proportional limit and yield point show an increase in some cases and a decrease in others, with increase of testing temperature. Further tests may decide to what extent either the composition or the state of the material is responsible for this fact.

For the first series of tests a carbon steel was chosen in order to form a basis on which the results found for alloy steels may in the future be compared.

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[1] Research Department, Westinghouse Electric and Manufacturing Co., East Pittsburgh, Pa.

[2] *Engineering*, 1924, No. 3029.

APPARATUS USED FOR HIGH-TEMPERATURE TESTS

Testing Machine—All the tests were carried out on the latest type of hydraulic 100,000-lb. tension testing machine supplied by the Alfred J. Amsler Co., Schaffhouse, Switzerland. The machine is equipped with an attachment for taking autographic diagrams. **Mr. Wilhelm.**

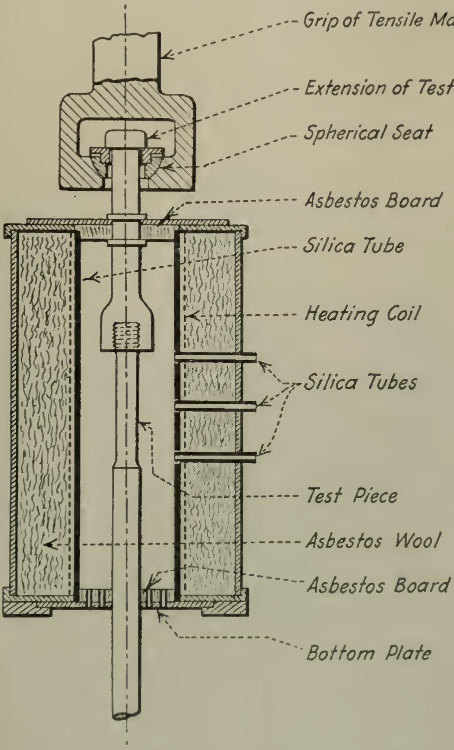

FIG. 1.—Electric Furnace for Tension Tests.
(Coil wound from $\frac{1}{8}$ by 0.032-in. nichrome wire; resistance, 125 ohms per 1000 ft.)

Shortly before executing these tests the machine was checked up by means of a standardizing box, supplied by the builder of the machine. The errors in the readings of the load applied by the machine proved to be within ±0.5 per cent.

Furnace and Temperature Measurements.—According to tests carried through by Welter,[1] for temperatures up to 500° C. and for

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[1] Forschungsarbeiten aus dem Gebiete des Ingenieurwesens, Heft 230, p. 11.

Mr. Wilhelm. the duration of the tests, no scaling occurs on medium-carbon steel which might otherwise affect the results. As a rule alloy steels show a greater resistance against scaling than plain carbon steels. Considering these facts, it was decided to use an air-bath furnace instead of a liquid. In many respects an air-bath furnace offers advantages over the liquid-bath furnace. In the first case the extensometer with the mirrors can be inserted from the bottom, and the mirror carriers and the mirrors are thus subjected to much less heating. Besides, an air-bath furnace is easier to handle before and after the test.

A section through the electrically heated furnace is given in Fig. 1. The furnace consists essentially of a silica tube, 2½ in. in inside diameter, 3 in. in outside diameter and 9 in. in length, the heating coil, an outer brass tube, 6 in. in outside diameter, top and bottom plates, and the necessary asbestos board and wool for heat insulation. The length of the furnace was limited by the dimensions of the machine. By means of the top plate the furnace is suspended from the test specimen. Sliding bottom plates are provided to remove the high-temperature extensometer during the test after having passed the proportional limit. The small silica tubes are inserted horizontally to take care of the thermocouples. Fig. 2 shows the coil unequally spaced to compensate for cooling at the ends. In addition

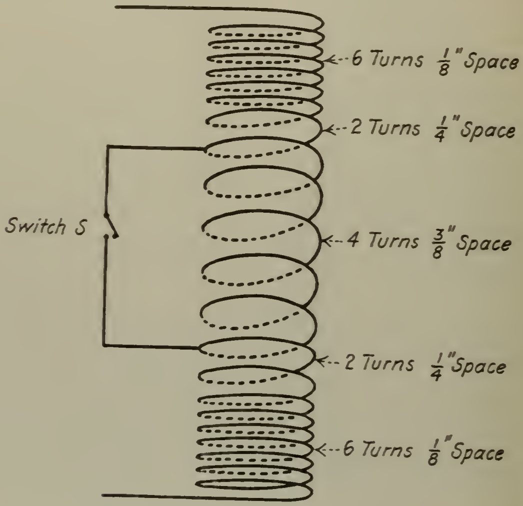

FIG. 2.—Coil Unequally Spaced to Compensate for Cooling.

Mr. Wilhelm

to this, several turns in the center can be put in parallel with a line of low resistance by closing switch S. In further development, switch S may be replaced by a resistance which would permit regulation of the amount of current going through each of these branches.

The thermocouple readings in the center of the furnace and at 2 in. distance toward top and bottom are given in the following table for three different ranges of temperatures:

LOCATION OF THERMOCOUPLE	TEMPERATURE, DEG. CENT.		
	200	300	500
Top	200	296	499
Center	197	300	502
Bottom	206	308	505

Comparison tests of thermocouples welded on, and others pushed against, the test specimen gave at the desired temperatures a difference of 12 to 25° C., the couple welded on the test specimen showing the lower temperature.

The test specimen being exactly in the middle of the furnace and the gage length with the fillets being 4 in. long, the thermocouples of the top and the bottom at 4 in. distance will coincide with the increased section of the test specimen, where due to conductivity a decrease in temperature was noticed. Therefore the top and bottom thermocouples proved to be more valuable in indicating the fluctuations of temperature rather than giving any absolute value, which exclusively was determined by the pyrometer in the middle of the gage length.

The materials used for the thermocouples were copper and advance. For taking the readings they were pushed slightly against the test piece. A potentiometer in conjunction with a calibration curve for the above mentioned metals was used for determining the temperature.

High-Temperature Extensometer.—The telescopes and the mirrors of the Martens mirror apparatus were used in the ordinary way for measuring strains. The comparison strips had to be subjected to a change in order to transmit the extension of the gage length outside of the furnace. This has been done on the same principle as in tests executed by other investigators and is shown schematically in Fig. 3.

Two rings with knife edges inside and V-notches outside secure the position of the comparison strips. Spring attachments hold the strips in their position. The mirror carriers rest in a V-notch on one strip and on a cylindrical surface on the other. In the design special care was taken that no part of the instrument was supported in more than three points to secure its position. Any extension between the

Mr. Wilhelm. points *A* and *B* will produce a displacement of the points *C* and therefore affect the position of the mirrors, and, in consequence, the reading on the scale through the telescope. With regard to the accuracy of the readings, the distance *AB* on the test specimen ought to be as long as possible; on the other hand, the difficulty of having a uniform temperature over a great length had to be taken into consideration. A length of 2.75 or 3 in. seems to comply best with both requirements.

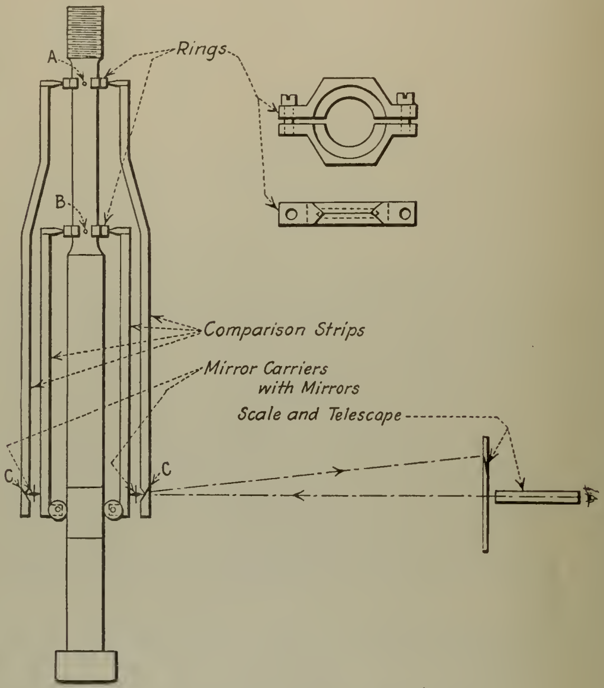

FIG. 3.—High-Temperature Extensometer.

The material used for the instrument had to show the following characteristics:

(*a*) Machineability;
(*b*) No scaling at high temperatures;
(*c*) Good tensile properties at high temperatures.

Stainless steel was considered suitable for the temperatures in question.

The instrument was compared with the normal-temperature Martens equipment and the difference found to be less than one per cent.

TENSION TEST SPECIMENS

Mr. Wilhelm.

The test specimens were machined from 2-in. diameter steel bars in pairs. In further tests a smaller diameter may be used in order to avoid the milling of the bars in the longitudinal direction. Fig. 4 shows a test specimen with the extension grip and the high-temperature extensometer mounted on it. The cylindrical part of the test specimen subjected to the test has a diameter of 0.505 in. and a length of 3 in., which are used for the extensometer measurements.

In order to determine the elongation, the whole length was divided in parts 0.25 in. long and a fine mark made with a center point. The fact that most of the test specimens broke between two marks and not in the marks may prove that there is no considerable influence on ultimate strength due to this dividing method. The value of elongation was determined for a standard gage length of 2 in. as well as for 3 in. and fracture was supposed to be in the middle. With the intention to save material and machining costs, further tests with grips on both ends of the test specimen will be made.

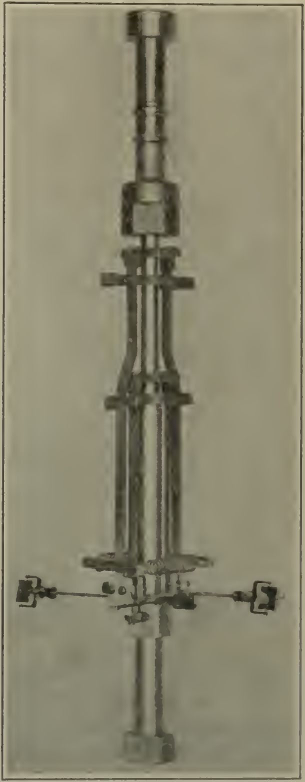

FIG. 4.—Test Piece with Extension Grip and High-Temperature Extensometer.

EXECUTION OF TESTS

After checking the main dimensions and dividing the gage length, the extensometer was assembled without the mirror carriers. The test specimen and instrument were inserted in the furnace and all together put into the tension testing machine. After putting the mirror carriers in place and adjusting the mirrors, a test was made at normal temperature and at a low stress (within the proportional limit) to insure that the extensometer and mirrors were set correctly. Heating

Mr. Wilhelm. of the furnace was then commenced, and after it reached the desired temperature, it was kept for at least two hours before the test specimen was put under load. Most of this time was necessary for an accurate adjustment of the electric current to maintain a state of equilibrium in temperature, the latter being indicated by thermocouple as well as by extensometer readings, provided that there was no, or at least no variable, stress on the test specimen. Then a gradually increasing load was applied and extensometer readings were taken at equal intervals. After passing the yield point, or after an equivalent increase in strain at temperatures without an accentuated yield point, the mirrors were removed. In order to avoid any disturbance of the constant temperature the comparison strips were removed only after passing the ultimate strength and previous to fracture.

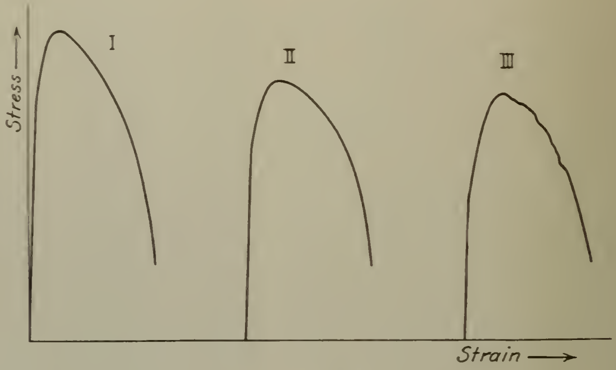

FIG. 5.—Speed Effect at 500° C., Medium-Carbon Steel.

Test number	I	II	III
Duration of test, min	6	70	240
Ultimate strength, lb. per sq. in	53 500	44 500	41 600

PRELIMINARY TESTS ON MEDIUM-CARBON STEEL

A series of tests was first carried out at various temperatures without the high-temperature extensometer. This showed an increasing effect of testing speed especially upon the ultimate strength. Fig. 5 shows the diagrams taken at 500° C. with different speeds, the durations of the whole test being 6, 70 and over 240 minutes, respectively.

Mr. Wilhelm.

A second series was carried out with the high-temperature instrument. Two speeds were chosen, one which just allowed readings being made and the other which was a very low one, that is, 1000 and 100 lb. increase of load on the machine per minute, respectively. This test, however, did not show a very distinct speed effect. This fact might have influenced Mr. French of the Bureau of Standards to use a photographic method for recording the stress and strain values at high testing speed.

For our test it was decided to use a normal testing speed and to study the time effect, especially of long time, on a separate apparatus.

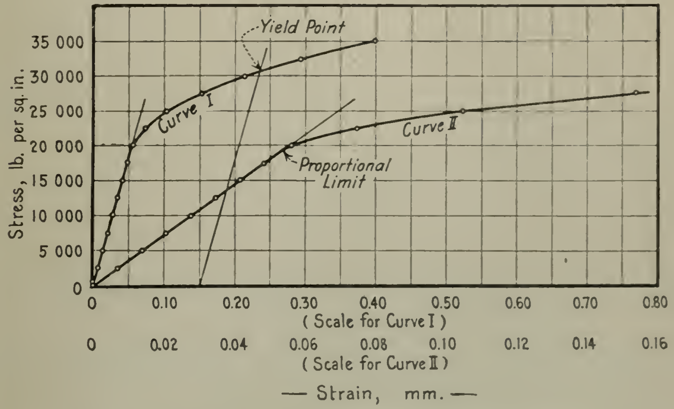

FIG. 6.—Stress-Strain Curve Illustrating Proportional Limit.

(Test piece No. 721–7, medium-carbon steel. Testing temperature, 300° C.; proportional limit, 19,500 lb. per sq. in.; yield point, 30,600 lb. per sq. in.; modulus of elasticity, 27,600,000 lb. per sq. in.)

Another phenomenon worthy of note is the fact that fracture of the test specimen occurred at the point of minimum temperature, provided that the ultimate strength increased with increase of temperature, and at the point of highest temperature if the ultimate strength decreased with increase of temperature.

PROPERTIES DETERMINED IN TENSION TESTS

The elastic properties, such as proportional limit and modulus of elasticity, were considered the most important features of the tests. In addition to these the values of yield point, ultimate strength, elongation and reduction of area were determined.

Proportional limit was defined as the stress value at which the stress-strain curve showed a distinct deviation from a straight line.

Mr. Wilhelm. It is necessary to add that the same scale for stress and strain had to be used in these determinations.

Since the yield point was not accentuated at higher temperatures, a certain method of expressing this value was adopted. In these tests, therefore, the yield point is taken as the intersection of the stress-strain curve and a straight line parallel to the line of proportionality and passing through the abscissa at a strain of 0.2 per cent of the gage length. That means that by unloading at this stress value the permanent set would amount to 0.2 per cent of the gage length.

This definition is widely adopted in European laboratories for materials without accentuated yield point. A point determined in such a manner gives valuable information with regard to the shape of the curve beyond the proportional limit. Fig. 6 shows the application of these definitions on a stress-strain curve, taken at a testing temperature of 300° C.

The modulus of elasticity was calculated from the formula:

$$E = \frac{\Delta P \cdot l}{s \cdot \Delta\lambda}$$

where ΔP = increase in load in pounds from reading to reading;
l = distance A-B in inches (Fig. 3);
s = section of test piece in square inches;
$\Delta\lambda$ = average increase in extension, from reading to reading up to proportional limit in inches.

The other values are determined in the usual manner and need no further explanation.

CHARACTERISTICS OF MATERIAL TESTED AND RESULTS OBTAINED

Chemical Analysis.—The material used for these tests was taken from the same heat and all the bars analyzed. The values obtained varied within the limits given below:

Carbon	0.37 to 0.40	per cent
Manganese	0.63 to 0.69	"
Silicon	0.11 to 0.14	"
Phosphorus	approximately 0.012	"
Sulfur	approximately 0.037	"

Phosphorus and sulfur were only determined from some of the bars.

Treatment of Material.—Before machining, the material (2 in. in diameter) was normalized at 875° C., soaked three hours at temperature, and air-cooled.

Discussion of the Results

Mr. Wilhelm.

From Fig. 7 the decrease in slope of the stress-strain curve with increasing temperature will be seen. As this slope determines the modulus of elasticity, it may be noted that there is only a slight

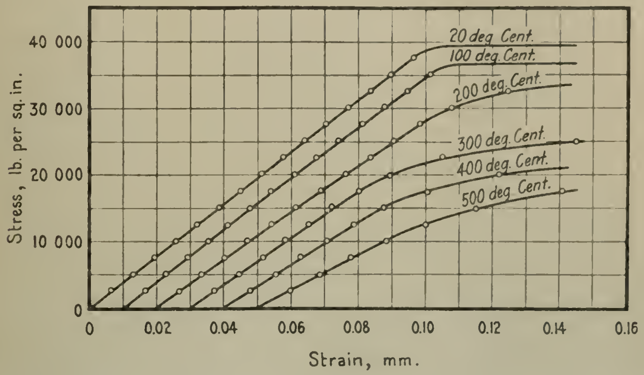

Fig. 7.—Stress-Strain Curves at Various Temperatures, Medium-Carbon Steel.

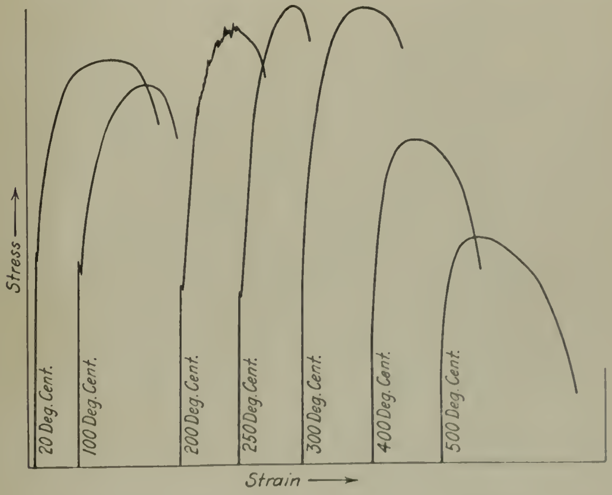

Fig. 8.—Autographic Diagrams for Various Temperatures, Medium-Carbon Steel.

decrease at the beginning and a more accentuated one at higher temperatures. Fig. 8 gives the reproduced autographic diagrams. The suppression of the yield point at temperatures higher than 260° C.

Mr. Wilhelm. is clearly shown. Furthermore, it is interesting to note that the diagram taken at 200° C. shows accentuated vibrations before reaching the ultimate stress. The same phenomenon was observed by Portevin and Le Chatelier.[1] These vibrations may partly be due to the pendulum of the testing machine, but it appears logical to state that a primary cause has to be sought in a change of the material itself.

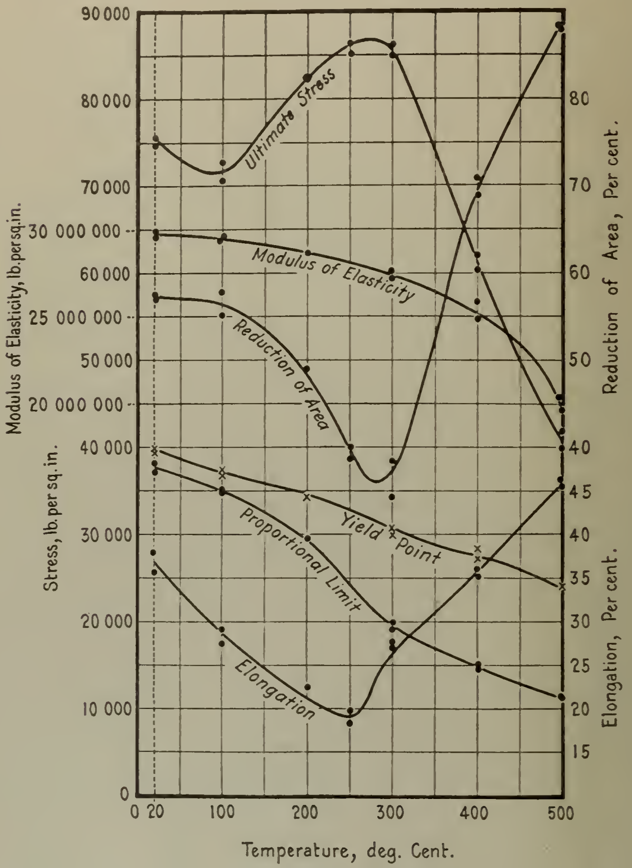

FIG. 9.—Tensile Tests at High Temperatures, Medium-Carbon Steel.

Fig. 9 gives the complete results of the tension tests. It will be observed that the curves of the proportional limit and yield point

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[1] *Comptes Rendus*, Vol. 176, p. 507.

show from the beginning a decrease in stress with increase of temperature. The ultimate strength shows a minimum at about 100° C., but attains a maximum at about 260° C., from where it falls sharply, up to the highest testing temperature. The curves for elongation (on 2-in. gage length) and reduction of area are of similar character, but it may be noted that the minimum elongation is reached at a somewhat lower temperature than that of reduction of area. **Mr. Wilhelm.**

The change in the modulus of elasticity expressed by the ratio E_t/E_{20} in which E_t = modulus at temperature t° C., and E_{20} = modulus at temperature 20° C., is given below:

	Temperature, deg. Cent.					
	20	100	200	300	400	500
E_t/E_{20}	1	0.987	0.961	0.920	0.853	0.657

On this occasion the writer wishes to express his indebtedness to Messrs. J. M. Lessells and S. Timoshenko for their valuable suggestions concerning these tests and to the Westinghouse Electric and Manufacturing Co. for the permission to publish these results.

Mr. Lester. Mr. H. H. Lester[1] (*presented in written form*).—Mr. Malcolm's reference to X-ray testing touches a field so new that no one can predict now the influence this method will have on production methods. Mr. Westgren in Sweden pioneered in the field of applying X-ray analysis to the structure of steel at high temperatures. Mr. Malcolm referred to the original article by Mr. Westgren. Since this was published he has continued this work and there was presented at the May, 1924, meeting of the British Iron and Steel Institute a further contribution along the same line. In this paper the previous results with regard to δ iron are confirmed. That is, there is a fourth critical point in the steel constitution diagram. Apparently molten steel in freezing changes to cubic crystals of the body-centered type. At around 1450° C. the body-centered cubes change to the face-centered cubic crystals characteristic of austenite. At around 760° C. the face-centered type changes to the body-centered type characteristic of α iron, the iron usually found at room temperature in ordinary steels. With regard to carbon in steel at high temperature, Westgren shows that the face-centered crystals of austenite are enlarged due to the presence of carbon. This indicates that the carbon atoms are forced into the interstices between the iron atoms at temperatures where γ iron is formed. Work by Bain, McKeehan, and others has shown that metallic solid solutions are formed by atoms of the solute replacing atoms of the solvent in the crystal structure of the solvent. Westgren's work points out the possibility of another type of solid solution

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[1] Research Engineer, Watertown Arsenal, Watertown, Mass.

Mr. Lester. in which the solute atoms are forced between the solvent atoms without breaking up its structure. According to this, alloy steels may be made up of three types of constituents, that is, mechanical mixtures of different metals and two kinds of solid solutions. In addition, we may have chemical compounds. Chemical analysis may be used to distinguish definite compounds, but nothing we know of except X-ray tests will distinguish between mixtures and the two types of solid solutions.

That a knowledge of solid solutions and mixtures is highly important in steel practice is indicated by the fact that in Watertown Arsenal four different solid solutions were found in a single specimen of high-speed tungsten tool steel. Control of these solutions probably will be effected through heat treatments. It is necessary to correlate the X-ray data with physical tests to determine the value of these solutions. This information is being gradually accumulated in the Watertown laboratories and elsewhere.

When we consider the various changes in structure that iron undergoes in cooling from the liquid state to room temperature, the fact that alloy constituents often tend to delay or prevent these changes, and the fact that different rates of cooling also affect these changes, we would expect to find in castings, particularly in chilled castings, metal that is by no means in a state of equilibrium. It may be full of partially completed physical reactions. These arrested developments are no doubt responsible for many physical peculiarities. Martensite is an example of arrested developments and its hardness is due to arrested physical reactions. X-ray investigation probably will slowly unravel the tangle of cast-metal structures and give us the knowledge to control to our profit these partially completed reactions.

Mr. Holz. MR. HERMAN A. HOLZ[1] (*presented in written form*).—Referring to the paper by Mr. Malcolm on the methods of testing metals at abnormal temperatures in which the periods of stress application must often be extended to hours, days and weeks, it will be of interest to mention here the special apparatus (Fig. 10) recently developed by Mr. Alfred Amsler for the automatic maintenance of a constant load, independent of the deformation of the specimen, in his well-known tension and compression testing machine. This load-maintaining device has been developed especially for research work on the physical properties of metals at elevated temperatures extending over long periods and operates automatically for any desired period, for days or weeks. It thus produces the same effect as the direct hanging of known weights onto a test specimen, as used by Dickenson in his high-temperature researches.

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[1] Testing Engineer, New York City.

The Amsler pendulum dynamometer with its self-contained **Mr. Holz.** "primary standard" of pressure measurement against which the load in the testing machine is automatically balanced during the entire testing operation is too well known to require a detailed description. The automatic load-maintaining apparatus consists of a very simple and effective electric-contact attachment to the load dial of this dynamometer. The contact is made and broken through the load-indicating pointer. The contact arrangement is connected to a mercury tilting switch and closes or opens the electric circuit. The apparatus actuates, through a solenoid, a device which stops the oil-pressure pump of the testing machine immediately the limit of load allowable is reached, and starts it again as soon as the oil pressure in the testing machine sinks below the lower limit which had been set. A movement of two

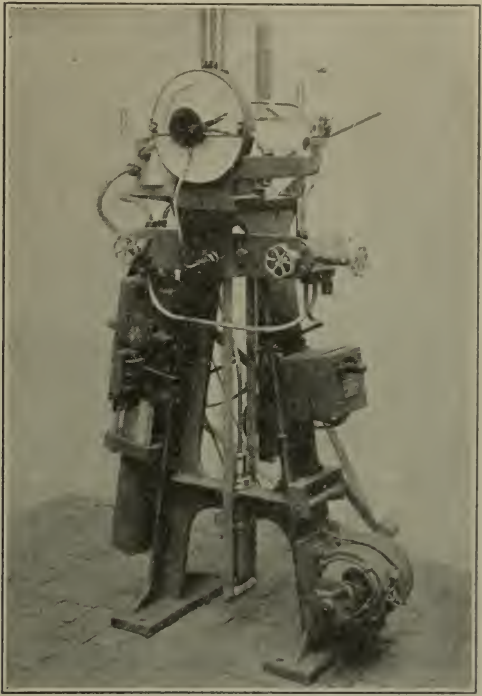

FIG. 10.—Amsler Pendulum Dynamometer with Apparatus for Automatic Load Maintenance, Independent of the Deformation of the Specimen.

Mr. Holz. millimeters covered by the pointer suffices for reversal. To prevent any abrupt action of the mechanism, a regulating valve is fitted in the pressure regulator.

Mr. Malcolm has described some of the difficulties usually encountered in attempting to obtain a uniform temperature over the entire length of a heated test bar. In the design of electric resistance furnaces of this type it may be useful to make the heating element not of one continuous wire spiral, but to use a number of separate wire spirals, arranged along the heating tube, with no electrical connection between the various sections making up the entire heating element. If each of these spirals is controlled separately by means of rheostats, it will be possible to obtain a uniform temperature over the entire length of the test bar. The influence of the cold-specimen heads which conduct a considerable quantity of heat away can thus be offset and eliminated.

There is one method of heating the specimens which Mr. Malcolm has not mentioned. The writer refers to the method of using the tension test specimen itself as resistor in an electric circuit of low voltage and high amperage, by the utilization of alternating current and a suitable transformer. If this method of heating could be successfully applied, it would possess the important advantage that the bars would be heated progressively from the inside toward the outer portions, and not *vice versa.* An arrangement of this kind may also simplify the application of optical extensometers.

Welter, who developed a special gas furnace for his researches, calls attention to the possible influence of magnetic induction, as produced by electric furnaces made from a coil of resistance wire, on the strength and elastic properties of steel specimens. He claims that his gas furnace, constructed in two parts connected by hinges for convenient opening and closing, permits a temperature regulation and maintenance to 0.5° C. at low and high temperatures. This accurate control, due mainly to the design of the furnace, is facilitated by the insertion of a pressure regulator in the gas duct. Although the tendency during recent years has been to apply electricity to the production of high temperatures in the laboratory, Welter points out the disadvantages of the electric furnace for this particular work in testing practice and describes means developed by him for producing and maintaining accurate temperature control by the use of gas which can hardly be improved upon, if at all equalled, by using electric current. If the writer is not mistaken, Welter's furnaces for use in testing machines are now being produced abroad on a commercial scale.

Regarding the methods to be applied in high-temperature researches on metals, there are two methods which we will have to develop for routine tests at high temperatures, while a third one will yield much information of value in research. The writer is referring, first of all, to hardness tests at elevated temperatures, because resistance to indentation under static load and strength of the material run more or less parallel. Unfortunately, the standard static Brinell test is not suitable under these circumstances, mainly for the reason that it does not produce impressions of geometric similarity, so that the results are not independent of the load applied and of the impressions produced. At normal temperatures this is not very serious; we can standardize the load applied and most of the other testing conditions. In working at high temperatures, however, we have to figure with considerable variations in the plastic properties of the materials under investigation, and we therefore cannot use a method which compares the various materials, in entirely different states of deformability, to entirely different degrees of deformation. **Mr. Holz.**

The writer believes that the Ludwik cone test, which does not possess these disadvantages, will be quite suitable for high-temperature tests and that Ludwik's researches on "the variation of internal friction of metals with temperature" can be extended from the non-ferrous to the ferrous field. The conical indenting tool as designed by Ludwik could be constructed from a suitable cobalt-chrome alloy. The application of the Ludwik test, in this instance, would certainly be preferable to the use of kinetic hardness tests as recently developed by Edwards in England and by Wuest and Bardenheuer in Germany. He does not believe that the various formulas at which these investigators arrived during their comparative static and kinetic ball-hardness tests at room temperatures will hold good at elevated temperatures. Furthermore, static tests such as Ludwik's will always yield data of greater accuracy and reliability than kinetic tests, because in static tests all forces applied and energy absorbed are under perfect control and measurable with accuracy.

The second routine test which is urgently needed, not only in high- but also in normal-temperature tests, is one permitting the determination of the elastic limit and of the limit of proportionality of metals exposed to impact forces. Mr. Malcolm calls attention to the important fact that it would be quite incorrect to use the tensile strength of metals at high temperatures as a basis of design. The writer believes that it would be still more dangerous, in many cases, to base the design of metal structures exposed to impact on the data of their resistance to fracture by impact. Almost nothing has been

Mr. Holz. done so far in elastic-limit determinations under impact, although it is undoubtedly of the greatest practical importance to study the impact elastic range of materials, at normal and elevated temperatures.

The third method, which the writer previously called a research method and which must be extended to the field of high temperatures, is the so-called "looping" method developed by Dalby. It is one of the most sensitive methods ever devised on the micro-structure of metals and is particularly suitable for investigation of the metals in their plastic state. Dalby's methods and researches are now so well known that it will not be necessary here to go into further details. Looping tests at high temperatures, by the use of the Martens optical extensometer, have been carried out on iron and copper by Mauksch in Germany, and valuable data have been obtained. It would be very desirable to extend these high-temperature looping tests to the alloy steels.

Mr. Marsh. MR. KIRTLAND MARSH.[1]—In order to make the data obtained by several observers comparable, the temperature of the test specimens should be accurately determined, and in some of the apparatus described in Mr. Malcolm's articles it seems improbable that the temperature of the specimens could have been accurately measured with the equipment arranged as shown. The results, given in the Symposium, of tests made by some of the observers show the temperature differences which may have existed in the test specimen and the differences in temperatures as measured by thermocouples mounted in different manners. Data on physical properties at other than room temperatures would be of much greater value if it were definitely known that the reduced section of the specimen was at a uniform temperature throughout, and that the temperatures given were the actual temperatures of the specimen. Therefore, since there may be some doubt as to the uniformity of temperatures throughout a test specimen and also as to the accuracy of the specimen temperatures as measured, every observer, not only for his own benefit but also to accredit the results of his work to others, should carefully determine the temperature gradient throughout the specimen and the accuracy with which the actual temperature of the specimen is measured.

A thermocouple measures the temperature of its hot junction, but if a temperature gradient exists close to the junction it can not be safely assumed that the hot junction is at the same temperature as another object, even closely adjacent to it, whose temperature it is desired to measure. In the case of a furnace where the holders or the specimen itself extend outside of the heating chamber, as is necessary

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[1] Pyrometric Engineer, Aluminum Co. of America, New Kensington, Pa.

Mr. Marsh.

for this work, a large amount of heat is conducted out of the furnace through the holders or specimen with the result that the temperature of the specimen easily might be 150° F. or more below the temperature of the medium surrounding it. Under such conditions, a couple with its hot junction held in contact with the specimen would probably indicate a temperature more nearly equal to the temperature of the medium surrounding the specimen than the temperature of the specimen itself, due to conduction of heat along the wires of the thermocouple to the hot junction. This is particularly liable to obtain in the case of a couple, the hot junction of which consists of a weld at the end of a twisted section of the wires, for in such a couple the hot junction would be at the first point of electrical contact between the two thermoelements, which in some cases might be at the beginning of the twist rather than at the welded portion. Even in the case of a couple welded without any twisting of the wires and placed in contact with the specimen there would be such poor thermal contact between the hot junction and the specimen that it is highly probable that more heat would be conducted along the wires to the hot junction than would be conducted from the junction to the specimen so that the junction would be at a higher temperature than the specimen.

The conduction of heat by the specimen or the holders extending outside the furnace cannot be eliminated, but it is perfectly possible to practically eliminate the conduction of heat away from that section of the specimen which it is desired to maintain at a uniform and constant temperature, namely, the reduced section. This can be accomplished if the heat, which ordinarily would be drawn from the reduced section of the specimen and conducted away by the holders or specimen extending beyond the furnace, is otherwise furnished by providing enough heat absorbing surface between the ends of the reduced section of the specimen and the ends of the furnace or by using auxiliary heaters around that part of the holders or specimen which projects beyond the end of the furnace.

If the conduction of heat away from the specimen is eliminated, a practically uniform temperature throughout the specimen can be secured and the temperature of the specimen, after temperature equilibrium in the furnace is reached, will agree more closely with the temperature of the medium adjacent to it. A radiation shield between the heaters and specimen may be found necessary in some cases. Under these conditions the temperature of the specimen can be easily and accurately determined.

To determine if the above conditions exist, a very careful temperature survey should be made and the following general method will

Mr. Marsh. serve this purpose. Locate thermocouples as shown in Fig. 11, the couples at positions 1, 2, 3, 5, 6, 7, and 8 being located with the hot junction on the longitudinal axis of the specimen and inserted as illustrated at (*a*) in the same figure. This latter shows a small-gage thermocouple with laid asbestos insulation and with a butt-welded hot junction. The couple is inserted in a hole, drilled diametrically through the specimen, with the hot junction on the center line of the specimen; a soft rivet driven into a second radial hole perpendicular to the first forces the hot junction firmly against the specimen, thereby making good thermal contact. The asbestos insulation on the wires extends inside the hole and prevents the wires from coming in contact with the specimen and forming another junction and also helps to retard heat

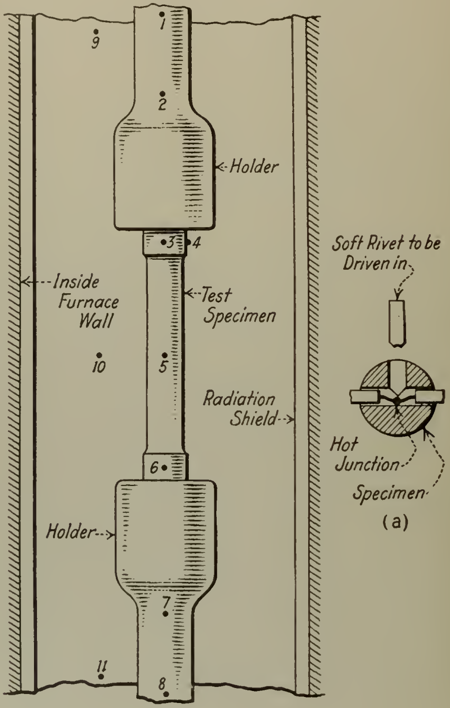

FIG. 11.—Location of Thermocouples in Temperature Survey of Test Specimen.

Mr. Marsh.

flow between the wires and surrounding atmosphere. This arrangement, it is believed, will measure the temperature at the center of the specimen very accurately.

Couple No. 4 is held against the specimen by as small a band as possible; the hot junction of this couple should be in the form of a bead flattened out a little with a hammer to provide greater contact surface. The bead should be in direct contact with the specimen but should be insulated from the band with a little asbestos and the two wires should touch neither the specimen nor the band. A couple attached in this way would satisfactorily measure the temperature of the specimen after the proper conditions have been attained and a comparison of the readings from couple No. 4 with readings from No. 3 during the survey will show how closely No. 4 can be relied upon to do so.

Couples Nos. 9, 10, and 11 are suspended in the medium surrounding the specimen and are for the purpose of indicating the temperature gradient from top to bottom of the furnace and to show how closely the specimen temperature agrees with the furnace temperature when equilibrium has been reached.

After the proper design of furnace has been attained there should be no temperature gradient within the specimen and only a very slight temperature difference between the specimen and the surrounding medium.

If it is deemed inadvisable to drill thermocouple holes in the holders intended for the actual physical tests, duplicate holders could be made up for the temperature survey.

In subsequent routine physical tests two thermocouples should be used, one at position 10 for furnace control and another strapped to the specimen as at position 4, to measure the temperature of the specimen. The difference between the readings from both will show when equilibrium has been reached. If auxiliary heaters are used around the ends of the holders or specimen projecting beyond the furnace two more thermocouples should be used to control the temperature in these heaters.

Mr. Moore.

MR. H. F. MOORE[1] (*presented in written form by T. M. Jasper*). —In the paper by V. T. Malcolm, reference was made to the methods used by the Investigation of the Fatigue of Metals (University of Illinois, National Research Council, Engineering Foundation, and various cooperating firms) for making fatigue tests of metals at elevated temperatures. The results obtained to date are regarded as tentative, but as a matter of interest they are summarized in Table I:

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[1] Research Professor of Engineering Materials, University of Illinois, Urbana, Ill.

Mr. Moore.

TABLE I.—ENDURANCE (FATIGUE) LIMITS OF STEEL AT VARIOUS TEMPERATURES.

TEMPERATURE, DEG. FAHR.[a]	ENDURANCE LIMIT, LB. PER SQ. IN.[a]	TEMPERATURE, DEG. FAHR.[b]	ENDURANCE LIMIT, LB. PER SQ. IN.[b]
70	36 000	70	105 000
555	39 000	330	96 000
715	42 000	580	85 000
875	44 000	845	78 000

[a] 0.49-per-cent carbon steel, normalized; tensile strength, 88,700 lb. per sq. in.; Brinell hardness number, 164.
[b] 1.02-per-cent carbon steel, spring temper; tensile strength, 200,400 lb. per sq. in.; Brinell hardness number, 415.

The slight increase in fatigue strength up to 875° F. for normalized 0.49-per-cent carbon steel checks results obtained by Mr. Lea of Birmingham, England. It is suggested as a hypothesis that within the range of temperature studied, increase of temperature has two contradictory effects: (1) Increased temperature tends to soften the steel and hence to reduce the endurance limit; (2) increased temperature tends to increase the ductility of steel and to diminish internal strain, and tends to retard or even to inhibit the formation and spread of fatigue fractures, and hence tends to increase the endurance limit. For the 0.49-per-cent carbon steel the latter tendency predominates, and for the 1.02-per-cent carbon steel the destructive tendency predominates. Of course, further tests are necessary to give a satisfactory basis for any theory. Such tests are now in progress.

Mr. Speller.

MR. F. N. SPELLER[1] (*presented in written form*).—Lap-welded steel pipe for steam pipe in boiler plants is now made (under the A.S.M.E. Boiler Code Specifications) of low-carbon open-hearth steel with average analysis and physical properties (at normal temperature) as given in the following table, which also includes data regarding the same grade of steel to which ferrophosphorus was added in the ladle.

	Chemical Composition				Physical Properties			
	C	Mn	S	P	Tensile Strength, lb. per sq.in.	Yield Point, lb. per sq.in.	Elongation in 2 in., per cent	Reduction of Area, per cent
Regular Open hearth	0.09	0.44	0.034	0.013	50 690	29 730	42.0	67.7
Rephosphorized (Open Hearth)	0.09	0.43	0.050	0.103	61.120	38 785	37.0	63.8

The tensile strength of this steel at normal temperature compared with the strength at higher temperatures is shown in Fig. 12, expressed in percentage of the original strength at normal temperature.

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[1] Metallurgical Engineer, National Tube Co., Pittsburgh, Pa.

Mr. Speller.

On the same chart is shown the strength of open-hearth steel of the same carbon content to which ferrophosphorus has been added in the ladle. These tests indicate that the latter retains a somewhat larger proportion of its original strength at the higher temperatures without much loss of ductility or resistance to impact.

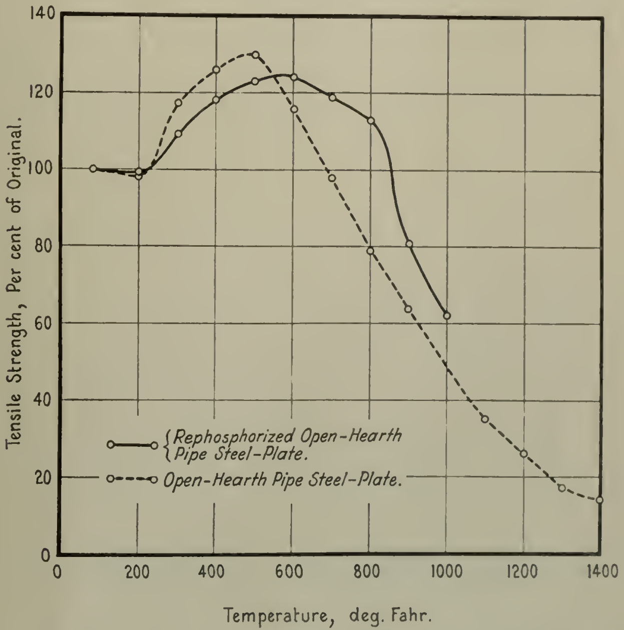


FIG. 12.—Effect of Temperature on the Longitudinal Tensile Strength.

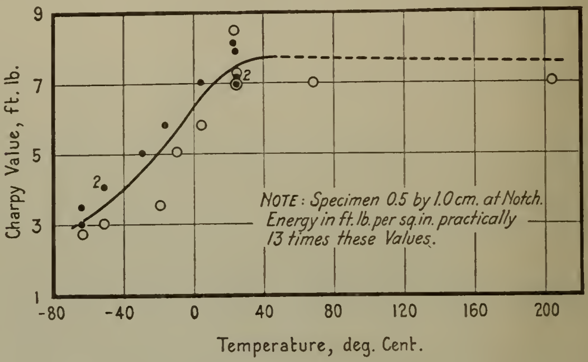
The average tensile strength of these steels at 1000° F., as determined from this test, is as follows:

Regular basic open-hearth pipe..................	26 500 lb. per sq. in.
Rephosphorized pipe.........................	36 000 " " " "

Attention is called to this, as phosphorus is one of the very few elements which can be added to welding steel without interfering with welding. Molybdenum seems to be another. In fact, the rephosphorized steel is easier and safer to forge weld, and apparently gives a sound steel equal to the regular open-hearth product with a much higher factor of safety. Endurance tests should be made on this steel.

Mr. Speller. The investigation now being carried out by the Joint Committee on Investigation of Phosphorus and Sulfur in Steel should determine whether in fact these elements have any detrimental effect when added to low-carbon steel which is originally low in these elements. If not, in the interest of all concerned the question of revising American standard specifications with reference to the sulfur and phosphorus limits should be considered without further delay.

Mr. Schwartz. MR. H. A. SCHWARTZ[1] (*presented in written form*).—The writer offers in Fig. 13 the results of tests made under his supervision by Messrs. W. W. Flagle and C. S. Fuller, which show the effect of low temperature upon the impact resistance of commercial malleable cast iron. These tests were made in connection with a problem which focused our attention upon the lower temperatures. They serve as a comparison, however, throughout at least part of the temperature range with the data of French and Tucker's Figs. 13 and 14.



NOTE: Specimen 0.5 by 1.0 cm. at Notch. Energy in ft. lb. per sq. in. practically 13 times these Values.

FIG. 13.—Notched-Bar Impact Resistance of Normal Malleable Cast Iron.

Open and solid circles represent metal from different sources.

It may be added that the results have been confirmed as typical of normal malleable cast iron by much other work in this laboratory. It is possible to produce malleable cast iron of still higher impact resistance by special methods, and equally possible to produce inferior material which suffers much more rapidly from brittleness as the temperature is lowered.

Mr. Puffer. MR. S. R. PUFFER[2] (*presented in written form by S. A. Moss*).—In the various tests reported of the physical properties of steel at

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[1] Research Department, National Malleable and Steel Castings Company, Cleveland, Ohio.

[2] Thomson Laboratory, General Electric Co., Lynn, Mass.

high temperatures, were the test specimens machined before or after heat treating? In other words, was any difficulty encountered in machining steel having high physical properties? **Mr. Puffer.**

In modern superheated steam and gas-turbine practice, it is very essential that the turbine buckets retain high physical properties at high temperatures. Dovetail shapes on such buckets are often very complicated. If heat treating is done after machining, hardening cracks are likely to be introduced. If machining is done after heat treating, will it not be necessary, in order to do the machining, to sacrifice a large percentage of the strength which might be available?

In Fig. 14 of the paper by French and Tucker, it is evident that high-nickel-chromium steel has excellent resistance to impact. Is any data available as to the tensile properties of this material at temperatures above 900° F.?

In Fig. 8 of the same paper, are shown two samples of tungsten high-speed steel, classified as B_1 and B_2, which show excellent properties at high temperatures. We understand that they have no elongation or reduction, even at the high temperatures, and are so hard that they could not be machined except by grinding. Is this correct?

Is any data available as to the high-temperature tensile properties of the high-nickel-chromium alloys, such as nichrome, chromel, etc.?

Mr. Strauss. MR. JEROME STRAUSS[1] (*presented in written form*).—The authors in their brief discussion of the chemical stability of steels and associated metals have touched upon a subject of extreme importance not only to the general engineering profession as we normally visualize it but of particular importance to the chemical engineer and his associates. Increased application, for production purposes, of high-temperature processes involving the reaction or production of chemically active materials, and the extension of the temperature and pressure ranges of these processes, have forced upon metallurgists the development of materials for progressively increased utility in these fields.

Even the service that has heretofore been obtained from ordinary metallic containers at atmospheric temperature no longer satisfies the requirements of continuous economical production. And in many cases metals have been required to withstand the action of corrosives through cyclic variations of temperature, pressure, and concentration over rather wide ranges.

The past decade has witnessed such rapid advances in the development of ferrous metals suitable under a wide variety of conditions

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[1] Material Engineer, U. S. Naval Gun Factory, Washington, D. C.

Mr. Strauss. of the above general nature, that the American Society for Testing Materials has seen the advisability of bringing together as much as possible of the available data on these new metals, and those which are at present in competition with them, in the form of a Symposium. A large number of papers have been secured for presentation at this meeting and it is believed that the discussion will be sufficiently extensive to create a broad fund of information relative to these metals. Mechanical, chemical, electrical and general physical properties are to be considered and, as an introduction, tables have been prepared giving manufacturer's data, in so far as available, concerning their various products. These tables should be of much value to the engineer in placing the entire commercial field before him and assisting in a selection of metals for specific applications.[1]

Mr. Fahrenwald. MR. FRANK A. FAHRENWALD.[2]—Referring to the paper by Messrs. French and Tucker, the writer believes greater emphasis should be placed upon the time factor as affecting the working strength of material at high temperature. The time factor as developed under tests running for only a short time does not give the effective strength of the material when subjected to stresses at temperatures above the recrystallization point.

Much of the information that has been hoped for and suggested by the various authors of these papers has already been worked out and has been available for some years to the trade. The physical strength of heat-resisting alloys at elevated temperatures has been determined in terms of permissible safe load stresses for use in design.

This property apparently has nothing to do with the elastic limit, nor is the modulus of elasticity in any way involved, and it seems that the fundamentals which govern the flow of viscous materials —such as ordinary road-paving pitch—have more to do with the behavior of these alloys at high temperatures than do the factors which we ordinarily associate with metals and alloys. A piece of road-paving pitch, placed between thumb and finger, can be slowly flattened with steadily applied pressure but if hit by a sharp blow with a hard object it will immediately fly to pieces like glass.

This same type of behavior seems to be common to metals and alloys as well. The rate of application of the load and the time during which it is applied are more important in determining the ability of an alloy to resist stress at high temperatures than all the other factors involved.

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[1] For the papers and discussions entering into this Symposium, see p. 189.

[2] Consulting Engineer, Cleveland, Ohio.

Mr. Fahrenwald.

The writer has determined the high-temperature characteristics of various steels, and particularly of alloys for resisting chemical corrosion and mechanical stress at high temperatures, and while some of this information is bound up in proprietary interests and professional obligations, most of it is available to any one who cares to ask for it.

At high temperatures the relationship between the apparent mechanical strength of a metal or alloy as revealed in ordinary tension tests, compared with the ability of the same material to resist continuously applied stress, is truly surprising.

At 1750° F., for instance, the strength of the nickel-chromium alloy, under a quick-pull test, will be more than fifty times that under a stress extending over a period of a year.

Most of the data that the writer has developed in this line are not taken from laboratory tests, but have been interpreted from practical commercial operations and with this information it is possible to design beams or structural members for operation at any given temperature up to, say, 2200° F. with the same assurance of success that obtains in the design of ordinary mechanical structures.

Thermal expansion is perhaps one of the most powerful and destructive agencies encountered in mechanical operations at high temperatures, due to dimensional changes that accompany changes in temperature.

In even the most simple mechanisms it is almost impossible to prevent temperature differentials of from ten to several hundred degrees between one point and another on the same alloy unit and as a result the cold part is under tension and the hot area under pressure with resulting plastic flow under either tension or compression, followed by a reversal of stresses perhaps with further temperature changes and final failure. Here is a problem of fatigue from alternating compression and tension beyond the plastic deformation limits of the material, and whether this corresponds to fatigue as we ordinarily understand it the writer does not know.

The problem of the application of metals and alloys at high temperatures is far more complicated and difficult than is ordinarily supposed. If physical strength or chemical resistance or thermal expansion or elastic limit or any one single factor is considered without correlating it to all of the other factors of the problem, failure will result.

These remarks may confuse the issue rather than clear it up, but this phase of engineering is indeed very complicated and anything

Mr. Fahrenwald. that will serve to call attention to the need for considering and correlating the numerous essential factors will be of help.

Mr. Christie. MR. A. G. CHRISTIE[1] (*presented in written form*).—The summary of the principal published work on the strength of non-ferrous alloys at various temperatures as presented by the authors indicates the increasing demand for alloys which will exhibit properties required by designers of apparatus which is stressed at high temperatures. The ideal condition as regards the strength of the material used in apparatus, such as valves and fittings, operating under superheated steam conditions would be that the physical properties remain constant from room temperature up to some point above the range of the temperature of operation. It is obvious that with such material the designers could be assured that no failure due to weakness would develop when the temperature is increased from normal to 800 or 900° F., which is above present operating temperatures.

In connection with securing data on such properties, it should be noted that where the curve of the elastic limit is falling off rapidly with increasing temperature, a slight experimental error in the measurement of the true temperature of the specimen affects its value for a given temperature to a very great degree. While allowance could be made by the designer for the decrease in strength of a material in which this property is affected by an increase in temperature as is the case in many steels and ferrous alloys, it is apparent from a study of the result of methods of testing and of values presented for various materials of this type that it is difficult to arrive at the exact amount of decrease of strength for a given temperature. Hence, it would be very much safer to use a material for which the curve of the elastic limit is nearly flat throughout the range of working temperatures.

Other considerations governing the choice of material by the designer or operator for valves and related parts subject to high temperatures are freedom from oxidation or corrosion and ability to grind the seat with facility.

Mr. Mochel. MR. N. L. MOCHEL[2] (*by letter*).—Referring to the paper by Messrs. Upthegrove and White, it may be of interest for us to record a peculiar type of failure which is apt to take place in the use of copper-tin alloys at elevated temperatures. A number of curves are given for copper-tin and copper-tin-zinc alloys, and in general there is a marked change, a sudden drop or a more rapid falling off in strength in the neighborhood of 450 to 500° F.

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[1] Consulting Engineer, Curtis Bay Copper and Iron Works; Professor, Mechanical Engineering, Johns Hopkins University, Baltimore, Md.

[2] Metallurgical Engineer, Westinghouse Electric and Manufacturing Co., Philadelphia, Pa.

Fig. 14 is a micrograph (×75) of a specimen of drawn phosphor bronze, containing 2 per cent tin and low phosphorus, after service for one year at 650° F. The stresses were quite low. There is a peculiar intercrystallin action which has taken place at the surface and is rapidly growing inward. The same condition has been observed on similar material after service at 500° F. The action has not been limited entirely to the drawn material, but has been observed as well on cast bronze of the 88-10-2 type, resulting in a falling away or deterioration of the metal and in the carrying away of "chunks" of the material, or its absolute failure. The action seems to be peculiar to those alloys of copper with low-melting point materials such as tin, although quite similar deterioration has been reported with copper-aluminum alloys at approximately 500° F. The action is marked by an embrittling of the affected material. **Mr. Mochel.**

FIG. 14.—Micrograph of Specimen of Drawn Phosphor Bronze.

The short-time tests may show fair strength for certain materials of the type mentioned above, at temperatures above 500° F., but deterioration is an item and must be considered.

It is also felt that a valuable and interesting addition to the Bibliography would be a paper presented before the Institute of Metals, in March, 1924, by Bunting, on "The Brittle Ranges in Brass." It has been summarized as follows:

"The brittle ranges exist in brasses of composition varying from 90 to 52 per cent copper. The brittle range of the 52-per-cent alloy extends from 220 to 540° C., and as the percentage of copper increases the range reaches a minimum at 57.5 per cent copper, extending from 320 to 450° C. With further

Mr. Mochel. increase of copper the range extends upward indefinitely, and at 65 per cent exists from 325° C. until the solidus is entered. At 75 per cent an upper limit to the range is once more observed, the range now extending from 350 to 725° C. Beyond this point the lower limit (hitherto practically constant at 325° C.) rises until at 80 per cent the range extends from 430 to 630° C. The range now narrows, and finally terminates in the neighborhood of 90 per cent."

Mr. Elliott. MR. GEORGE K. ELLIOTT[1] (*presented in written form*).—There is need of close cooperation between chemist and metallurgist in our present problem of metals for high-pressure and high-temperature steam. At present the metallurgist is given little other information than the temperature and the pressure at which the central station is to be operated, and possibly this information is sufficient, but the writer for one would like to have fuller data concerning the chemical composition of this new steam which our metals are to handle.

Endless literature has been written about the chemistry of the boiler and boiler waters and the most of it is of great value, especially in studying corrosion, but if we search for information concerning the chemical reactions which do or are likely to take place in boilers operating at the new pressures of 400, 600, 900 lb. per sq. in. or even higher, we are doomed to disappointment; little is available. The reason for laying stress on this is that the writer feels insufficiently assured that the chemical reactions taking place in water containing certain dissolved salts and gases, at 100-lb. pressure and 337° F., are going to take place when the pressure is raised to 400 or 600 lb. and the temperature to 750° F. Will the steam generated under the new conditions contain compounds which were not present in the vapor from the old-fashioned boilers?

Only one possible but admittedly speculative condition will be given as an example. Some investigating chemist in England, I believe, has made somewhat of a study of this new boiler chemistry and is on record as having evidence that alkaline boiler water containing sodium carbonate, for example, under certain conditions of concentration, pressure, and temperature, will react to form a series of organic acids such as formic, glycollic, and others of a series made by successive deductions of an atom of oxygen from the compound. This is extremely interesting if true, and even more so when we are told that there is a possibility that volatile organic compounds of a corroding nature such as formaldehyde may be formed in the boiler. If, therefore, it is discovered that corrosive compounds of a kind hitherto unknown to boiler chemistry are likely to be formed in high-pressure boilers, the metallurgist should have definite information

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[1] Chief Chemist and Metallurgist, The Lunkenheimer Co., Cincinnati, Ohio.

Mr. Elliott.

concerning the exact nature of these new ingredients in the steam to be handled by this metallic piping, valves, fittings, and turbines.

It may be that there is no real cause for alarm, but the writer would like to see the question of boiler-water chemistry thoroughly studied by competent chemists, preferably organic chemists, since the reactions foreseen are of a decidedly organic chemical nature. There is a probability that the new high-pressure boilers are chemical manufacturing units, operating on the dissolved substances of the water, in which a great number of complex reactions probably take place with the production of many compounds, some of which may well be viewed with suspicion by the metallurgist who is prescribing metals to handle these chemical products when mixed with steam.

Once the program of purely chemical research is completed, and the chemical nature of the impurities in steam generated at high pressures and then superheated is determined—if such impurities be found—obviously the next step would be to conduct high-temperature physical tests with the test pieces immersed in atmospheres which are similar to the steam we are describing. This would add immeasurably to the labor and time necessary for making these tests, especially the time, for time would be important directly in proportion to its duration; but the results might well prove to be worth all the trouble multiplied many times. The writer is not ready to predict how important the matter of surrounding atmosphere may be in making these high-temperature tests upon all the metals and alloys now used in handling steam, but it has been demonstrated by Bengough and Hanson that in the matter of copper it is of the greatest importance. So-called season cracking, so frequently met with in wrought non-ferrous metal, also is somewhat related to the point of this discussion. It was shown some years ago that this kind of metal failure has its beginning with surface corrosion of the piece under stress, the corrosion being caused often by gaseous impurities of a corrosive nature in the surrounding atmosphere.

To sum up, the writer suggests the following research:

1. That chemical reactions in high-pressure boiler water and in superheated steam, up to 800° F. be investigated;
2. That, if corrosive compounds are found to be a possibility in such steam, high-temperature physical tests be made with test specimens surrounded by an atmosphere similar to this steam.

Mr. MacPherran.

MR. R. S. MACPHERRAN[1] (*presented in written form*).—As many plants are operating with steam at from 800 to 850° F., it is necessary

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[1] Chief Chemist, Allis-Chalmers Manufacturing Co., West Allis, Wis.

Mr. MacPherran. for us to know the properties of materials at these temperatures. Until recently, most high-temperature testing was done by heating the specimen until the desired temperature was reached, and then running the usual tension test. As referred to in these papers, however, Mr. Dickenson has made a series of most interesting tests by maintaining a constant load and a constant temperature until failure of specimen. We are preparing to make tests along these lines and hope to work under various temperatures and loads.

We are now making some tests along a little different line by holding the specimen at constant load and slowly increasing the temperature until failure occurs. In each test, the specimen was held at a definite temperature until the beam remained in balance for 15 minutes. This would allow for any expansion due to increased temperature, and for any extension which might take place in this short period. The final period or period of maximum temperature before failure at this increasing temperature and constant load lasted several hours or more. For example, one specimen was held at 1000° F. under a load of two-thirds of its elastic limit for over 15 hours before it finally failed. The load was maintained, of course, during the entire test by keeping the beam in balance as the specimen elongated. While our results in these tests have been very interesting we are not yet in a position to report.

We would be much interested in learning how the various bronze test specimens were prepared. Were they cast or rolled? And was any trouble found in obtaining a uniform material? We have cast several sets of bronze bars for high-temperature tests but find great difficulty in obtaining specimens of the necessary uniformity for a series of these tests.

One of the most interesting ideas in this discussion is that advanced by Mr. Elliott.[1] We have all seen examples of steam corrosion for which there seemed to be no explanation or definite cause. It is possible that investigation of the chemical combinations formed in the boiler under high temperatures and pressures may lead to the solution of some of these problem.

Mr. Lincoln. MR. J. C. LINCOLN[2] (*by letter*).—This contribution to the discussion is at the request of the American Welding Society. It has to do with the action of metal deposited by the metallic arc and the effect of repeated heating on such metal. The metal deposited by the metallic arc process has a tensile strength of about 50,000 lb. per sq. in., if properly deposited. The ductility of this metal is low, about 5 per cent.

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[1] See preceding discussion.

[2] Lincoln Electric Company, Cleveland, Ohio.

Repeated heating of such weld metal in an oxidizing atmosphere at a temperature of about 1550° F. changes the structure of the weld metal and decreases both its strength and ductility. So far the writer has been unable to assign the cause for the change in structure and **Mr. Lincoln.**

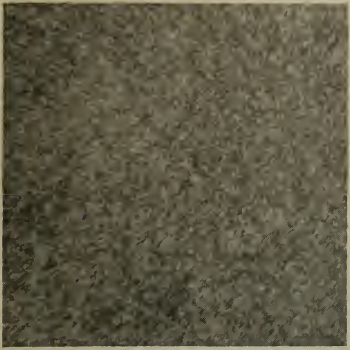

FIG. 15.—Microphotograph of Metal Deposited by Metallic Arc, After Polishing and Etching (× 100).

FIG. 16.—Microphotograph of Same Metal, After Repeated Heating at About 1500° F. (× 100).

FIG. 17.—Microphotograph of Ordinary Open-Hearth Low-Carbon Steel, Exposed to the Same Heating and Cooling (× 100).

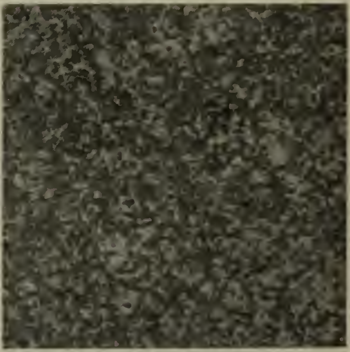

FIG. 18.—Microphotograph of Same Metal, After Repeated Heating at About 1500° F. (× 200).

for the change in physical properties. If anyone has done any work along this line and can throw some light on this problem, he will be doing the art of electric welding a service.

Fig. 15 is a microphotograph of metal deposited by the metallic arc after polishing and etching.

Mr. Lincoln. Fig. 16 is a microphotograph of the same metal after repeated heating at about 1500° F.

Fig. 17 is a microphotograph of ordinary open-hearth low-carbon steel after having been exposed to the same heating and cooling that produced the change in structure shown in Fig. 16.

Fig. 18 is a microphotograph of the same sample shown in Fig. 16, except that the magnification is 200 diameters instead of 100 diameters.

Mr. Moss. Mr. Sanford A. Moss.[1]—The temperatures of 700 to 800° F. mentioned in the papers are really quite moderate. Mr. Emmet[2] mentioned temperatures of 1000° F. in connection with the mercury turbine. There now exist a number of gas turbines in series with internal-combustion engines, with wheel rotating at high speeds, and operating at temperatures of about 1000° F. Hence, the authors of the various papers must not stop at 700 or 800° F. but must go on.

One important point is proof that the specimen has the temperature alleged. Many of the tests in the bibliography cited are worthless because there is nothing to show that they do not fall in the large group of tests with erroneous temperature measurements. One way to be certain that the specimen has the supposed temperature is to make two separate sets of tests with two separate furnaces, one with a certain length of furnace and specimen, and the other with the same length of specimen and a longer furnace. If the same results are obtained reliance can be placed on them. No high-temperature tests can be given credence unless there is given actual proof in some such way of the validity of the temperatures.

It is quite possible that the time element which has been mentioned is largely a matter of thermal equilibrium. In other words, it may be that some of the experimenters who have thought that their results showed the effect of the time element really did not have conditions of thermal equilibrium originally, so that the effect was one of temperature measurement error only. The certainty of the time element can be established only when it is first proved that the temperature of the specimens is the temperature alleged.

Very little attention has been paid to the hardening and drawing temperatures for the ferrous materials tested. It is probable that, in order to secure the best performance at given high temperature, there must be quite a different combination of hardening and drawing temperatures than for some other temperatures. This, of course, opens up a vast field for research. In other words, it is possible that for every temperature of use of ferrous materials, there must be a special hardening and drawing temperature.

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[1] Engineer, Mechanical Research Department, General Electric Company, West Lynn, Mass.

[2] Discussion of paper by V. L. R. Emmet, "The Emmet Mercury-Vapor Process," *Transactions*, Am. Soc. Mechanical Engrs., Vol. 46 (1924).

Mr. Moss. The matter of the effect of the atmosphere on the testing has been mentioned. It is sufficiently difficult to make tests at high temperature without the added complication of having to maintain a certain atmosphere. The only materials in which we are interested for high temperatures are materials which will not be affected by the atmosphere. An independent set of tests could be made at high temperature in a given atmosphere, without any tension tests, simply to establish as to whether or not the material was affected. If it is found that the material is affected at the temperature involved, there is really little use of making further tests. If it is found that the material is not affected, then the high-temperature tension tests may be made.

Mr. Funk. Mr. Nevin E. Funk.[1]—This Symposium adds to our knowledge of the performance of materials at high temperatures, but the writer questions the advisability of using the exact values given on account of the fact brought up by other discussers, that it may not be possible to duplicate the results with different apparatus.

Since we are following practice with knowledge rather than knowledge with practice, and since the possibilities of considerably higher temperatures are of great interest in obtaining better efficiencies, material manufacturers should not consider the problem solved, but should endeavor to produce materials that will withstand these high temperatures better than the ones that are now available.

This Symposium apparently does not contain information as to the effect of temperature variations over a continuous period on the performance of these materials.

It is generally known that cast iron, unfortunately, grows at temperatures as low as 550° F. so that in, say, eight years' time, parts made of that material must be replaced. With these higher temperatures, the same thing may happen to steel or steel alloys. We have not yet had enough practical experience to know, but the field should be investigated.

The effect of oxidation on these metals at high temperature has been touched upon. If the higher temperatures produce more rapid corrosion, the factor of safety may soon become inadequate.

While all the information that has been presented is valuable as an indication of the trend of the subject, so far as the writer's personal feeling is concerned, only a beginning has been made toward the developments necessary to the intelligent design of higher temperature stations and the certainty that the life and safety of these stations will be as accurately anticipated.

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[1] Operating Engineer, Philadelphia Electric Company, Philadelphia, Pa.

Mr. Orrok.

MR. GEORGE A. ORROK.[1]—From the standpoint of the power engineer this subject presents three distinct problems dealing with (1) the turbine blade and the interior of the turbine, which remain at practically one temperature as long as the machine runs; (2) the boiler, whose external temperature may be quite high while its internal temperature is limited to the steam temperature used; and (3) the steam pipe, in which the internal temperature is fixed while that outside varies.

In regard to the first of these problems, materials which we have been using apparently stand any temperatures that have been attained so far and probably materials can be obtained which will permit turbine blades to be operated up to 800, possibly 900° F. Whether we shall be able to find materials for the gas turbine with its higher temperatures is something to be worked out.

As for the boiler, the outside of the metal may be heated to almost any degree. The writer recently had the opportunity of looking into a boiler where the internal surfaces were at a bright red heat. Probably the temperature of those internal surfaces was 900 or 1000° F., since the temperature inside the boiler was about 850° F. What happens in such cases is not known and much good work must be done before reliable information can be obtained.

Regarding the steam piping, it appears that materials are fairly well understood and perhaps pipe manufacturers will be able to provide almost anything that may be needed in the next twenty-five or thirty years.

One of the particular things in this kind of research is getting specimens of material which are alike and in duplicating them in the actual material that we buy to put into our plants. The writer is very certain that most of these specimens which have been tested, while ostensibly of a reasonably close chemical composition, are not alike, and probably two pieces cut from the same bar will show rather wide variations, both in chemical composition and in crystallin structure.

Mr. Robinson.

MR. ERNEST L. ROBINSON.[2]—The writer calls attention to a point which has not been emphasized elsewhere in the Symposium, namely, the importance of the effect of temperature on the modulus of elasticity. The other discussions deal with questions of strength, proportional limit, and extension, but in tuning a turbine wheel so as to control its natural frequencies of vibration, it is important to have information as to the modulus of elasticity. We have thought here-

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[1] Consulting Engineer, New York City.

[2] Turbine Engineering Department, General Electric Company, Schenectady, N. Y.

tofore that, throughout the temperature range to which turbine wheels are subjected, the change in modulus of elasticity is so gradual as to be of little importance. But some of the curves presented in these papers show rather sudden changes in the modulus. If these indications are substantiated, it will be important to give attention to the modulus in future investigations of the effect of temperature on steels. **Mr. Robinson.**

Mr. C. C. Trump.[1]—To Mr. Orrok's three and Mr. Robinson's one problem the writer would like to add a fifth. That is the problem of the oil refinery which has been referred to already in the papers. We not only have boilers, turbines and piping for steam but we also have stills which carry oil vapors at increasingly high temperatures and pressures. Within those oil vapors are associated not only high temperature and pressure, but also corrosive media such as sulfurated hydrogen and other gases which at those temperatures do attack the metals. In fact, they attack them to such an extent that we have to make our pipes thick enough to withstand a considerable reduction in thickness. Our problem of strength is one of years. We want to know about strengths of material at high pressures, and we hope that there will be further information coming along these lines. **Mr. Trump.**

Another point in which we are interested is the growth of materials other than cast iron, especially of the non-ferrous metals, because we sometimes want to use non-ferrous alloys in our valves and fittings. There is nothing in any of these papers concerning the growth of materials other than cast iron.

Mr. Samuel L. Hoyt.[2]—The writer would like to point out a certain relationship which he believes to be a general one connecting the load on a specimen and the life of the specimen at that load. **Mr. Hoyt.**

He first experimented on tin, a metal which is fairly soft and plastic at room temperature, with loads varying over a considerable range, so that the time element varied from less than one second to over a million seconds. In order to interpret the data he plotted them two or three different ways and finally found that if the logarithm of the time were plotted against the square root of the load the result was a straight line. That such a straight-line relationship is desirable can be shown very briefly.

According to one method of plotting the data, all of the points came on a smooth curve. When the data were plotted as a straight line it was noticed that the time for some of the loads was twice what it should be, according to the straight-line relationship. By exam-

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[1] Engineer of Tests, The Atlantic Refining Co., Philadelphia, Pa.

[2] Research Laboratory, General Electric Co., Schenectady, N. Y.

Mr. Hoyt. ining the samples it was seen that they had fractured according to a different method than the samples which had longer lives. This indicates that tin extends and fractures according to two different mechanisms, depending on the rate of deformation.

The writer has also noticed a difference between cold-worked metals and annealed metals in the way they follow this relationship, and, further, that the relationship holds over a wide range of temperature. He has examined tungsten at high temperatures and is beginning to examine iron and other metals at a somewhat lower temperature. From these observations the relationship seems to be a general one.

The writer suggests that those who are interested in this particular feature plot their data as the square root of the load against the log of the time. In that way, if there are any exceptional conditions present they will probably be brought out at once by the fact that the points do not fall on the curve or do not come as close to the curve as they should according to the experimental error involved.

A long-time test at a high temperature is not a simple thing, but if we knew that this relationship held, it would be possible to extrapolate from high loads, in order to get the probable life at low loads.

Mr. Templin. MR. R. L. TEMPLIN.[1]—We have been taking temperature tension tests on aluminum and some of the alloys of aluminum from time to time during the past five years. In general our results on pure aluminum check fairly well those given in the Symposium.

In connection with such tests it should be noted that in the material which was used by Messrs. Upthegrove and White there existed an appreciable amount of cold work. If the material had been annealed to start with, the tensile strength curves would not be parallel to the curve given in their paper. If the plotting of the data, however, is done so as to give the ratio of the tensile strength at any high temperature to tensile strength at room temperature, there would be fairly close agreement of results. That is, differences due to different amounts of cold working and perhaps even variations in composition of the material will be practically eliminated by such a method of treatment, usually in a very satisfactory manner.

It has been observed that tests on the cold-worked metal tend to give higher values for the range of temperature in which we are normally interested for design purposes. It is thought, however, that if the specimens were maintained at these higher temperatures for a

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[1] Chief Engineer of Tests, Aluminum Co. of America, New Kensington, Pa.

Mr. Temp

considerable period of time, varying with the temperature, the values obtained would approach those which are normally obtained, starting with annealed material.

In addition to the work that has been done on pure aluminum, we have done some work comparatively recently on pure magnesium and one of its alloys. In connection with these tests, it has been interesting to note that while we obtain one set of data with pure magnesium and another set of data with a magnesium alloy consisting approximately of 4 per cent aluminum, yet when treated in the manner just indicated, the tensile strength results are identical.

In applying these data in a practical way our inclination is first to evaluate the effects of temperature upon the material, then for design purposes to use in our formula the annealed tensile strength of the material at room temperature and show the effect on it rather than to take the tensile strength of some harder or cold-worked metal and depend upon that as the basic value.

We have run into serious difficulties in our methods of testing because the materials with which we have been concerned have a rather high thermal conductivity. This, of course, tends to decrease the difference in temperature that exists between the center of the specimen, say, and the outside surface, but at the same time it is harder to keep the temperature uniform throughout the length of the specimen. Again, the values for ductility or elongation are rather high in these materials, running sometimes over 200 per cent. That means that furnaces used in testing them must be quite long in order to maintain the specimens at the desired temperatures throughout.

We ordinarily consider these data as being roughly divided into two phases. The first is the one which extends usually to about 400° C. Temperatures from below room temperature to this point are the ones which concern the designer. Those beyond that point are usually of prime interest only to the manufacturer of such materials.

Mr. Jeffri

MR. ZAY JEFFRIES.[1]—Probably in all the fields for the use of materials at high temperature there is none in which so much effort has been spent as in the electric-lamp field. Artificial illumination with incandescent lamps depends upon the maintenance of a body at a very high temperature and for a considerable time. The tungsten filaments used in incandescent electric lamps sometimes reach a temperature of 2900° C. and are maintained at that temperature over a period of at least 100 hours, and some lamps with a temperature of 2700° C. may maintain their temperature for 1000 hours.

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[1] Metallurgical Engineer, Research Bureau, Aluminum Co. of America, Cleveland, O.

Ir. Jeffries. The material used is nearly a pure metal, about 99.9-per-cent tungsten. The writer calls attention to the effect of grain size on the maintenance of the characteristics of the metal at a high temperature. If the grains are maintained small at the high temperature the filament sags during the course of its use and the coils get out of shape. If a special treatment is made so that a larger grain size is produced, the elastic limit of the material is relatively high at a temperature just under the melting point and the coils maintain their positions. That has been found generally true, not only in tungsten but in other metals, and would indicate that at very high temperatures we should strive to obtain large grains in pure metals in order to maintain permanency of shape of the material.

There are so many complications in the temperature effects of pure metals that one hesitates to bring in the added complications of alloys, but they must be considered because they are important commercially. In alloys, the inter-metallic compounds are the hard constitutents at high temperatures. They correspond in high-temperature properties more to the non-metallic substances like fire clay or silica. They are the hard bricks which strengthen the soft metallic matrix in materials at high temperatures.

The writer compliments Mr. Wilhelm upon the determination of the proportional limit and the modulus of elasticity of steel at various temperatures. The subject of the modulus is one which has been worrying people for a long time, and the true proportional limit is one which is masked by the blue heat effect in iron. His results are certainly the best that have been seen in that field, and the writer looks forward to seeing further results from the same apparatus.

In conclusion the writer suggests that the general research be divided into two groups, as follows: First, the fundamental properties of materials at high temperatures, which may be carried on by the metallurgist and chemist; and second, the use of materials at high temperatures. The latter study may involve tests simulating use tests, and should be made by the engineer who is in close contact with the actual utilization of the metals at high temperature.

Ir. Iathews. MR. JOHN A. MATHEWS.[1]—As manufacturers of these materials, we have found some which proved to be tough at the lowest temperatures and malleable at liquid air temperature, while others showed only an oxidation film (similar to the temper colors of a tool) at 2200° F. We have worked out a series of them for various conditions of corrosion, a point that has been only slightly touched upon in this Symposium.

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[1] Vice President and Metallurgist, Crucible Steel Co. of America, New York City.

Mr. Mathews. There is no one material that will answer all purposes. For each of the milder acids—acetic, formic, lactic and butyric—we must meet the condition of maximum serviceability through special compositions. We have studied our products one at a time to attain maximum resistance to corrosion for scores of reagents under various concentrations and temperatures. In some cases a single material answers for many of them but not for all. For use at temperatures from 700 to 1600° F. these nickel-chromium-silicon alloys, known under the trade name of "Rezistal," seem to be stronger, tougher and more resistant to fatigue than any other type of ferrous or non-ferrous alloy.

Mr. Spring. MR. L. W. SPRING (*Author's closure*).—In discussion, several have referred to possible inaccuracy of results due to uneven heating of the specimens, loss of heat through conduction, difficulties of temperature measurement, etc. I think that no one realizes more than the investigator himself, who has tried to do some of these things and to do them as accurately as he can, the difficulties that are in the way of obtaining accurate physical properties of materials at high temperatures. One would be unwise to claim that any of the work done is perfect. Since all who have worked in the high temperature field have proceeded along more or less different lines, and since, therefore, there has never been anything like a standard method of making such tests, it is highly desirable that some properly formed committee very carefully work upon and determine the most satisfactory method or methods of high temperature testing, so that, hereafter, such routine testing may be done according to something like standard methods.

A point was made by Mr. Herman Holz regarding the possible effect of magnetic induction upon the results. Years ago in our laboratory we made tests along that line, using coils that were exact duplicates, except that one was our usual heating coil of nickel-chromium or nickel wire and the other coil was wound with pure copper wire, which gave only 12° F. rise in the bar, when using much greater amperage than we ever applied in actual work. These results were reported in 1912[1] but are repeated here in the accompanying Table II. As is shown by the figures, on neither brass, bronze, ferro steel, nor cast iron do results differ from results obtained without any coil at all, showing that the effect of induction is negligible.

Mr. Morrison referred to insulation of the holders. I believe that such has not been done commonly, so the holders and heads of the testing machines are constantly conducting away considerable amounts of heat, which, of course, means less equal temperature throughout the length of the bar or at least difficulty in maintaining equal tempera-

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[1] *Valve World*, January, 1913; Also References 83 and 216 of the Bibliography appearing on page 124.

TABLE II.—EFFECT OF ELECTRICAL CURRENT WITHOUT HEAT ON STRENGTH OF TEST BARS.

Material	Test	Tensile Strength, lb. per sq. in.	Elastic Limit, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent
Crane Valve Brass	Test I[a]	30 800	19 900	12.5	21.8
		30 800	18 900	18.8	19.2
		Average 30 800	19 400	15.7	20.5
	Test II[b]	31 600	18 775	15.6	19.6
		30 800	19 150	15.6	19.3
		Average 31 200	18 960	15.6	19.5
	Test III[c]	30 120	18 180	12.5	......
		Average 30 120	18 180	12.5	......
	Test IV[d]	32 300	21 000	15.6	18.9
		32 000	19 600	14.1	16.5
		Average 32 150	20 300	14.9	17.7
Crane Hard Metal	Test I[a]	38 500	23 430	7.8	14.6
		36 700	26 010	9.4	16.3
		34 180	27 000	9.4	15.1
		Average 36 480	25 480	8.9	15.3
	Test II[e]	35 350	......	9.4	......
		36 950	23 130	9.4	13.9
		37 100	26 745	12.5	16.6
		34 200	27 600	6.3	9.9
		Average 35 910	25 825	9.4	13.5
Crane Ferro Steel	Test I[a]	39 135			
		35 130			
		32 710			
		36 920			
		37 210			
		Average 36 220			
	Test II[e]	38 640			
		40 270			
		35 900			
		38 000			
		34 650			
		Average 37 490			
Crane Cast Iron	Test I[a]	23 700			
		21 960			
		Average 22 830			
	Test II[e]	21 750			
		23 800			
		Average 22 775			

[a] Without coil.

[b] With copper wire coil; $\frac{1}{2}$ ampere, 690 ampere turns. Broke at once.

[c] With copper wire coil; $\frac{1}{2}$ ampere, 690 ampere turns. Current on 5 hours.

[d] With copper wire coil; $2\frac{1}{2}$ amperes, 3450 ampere turns. Broke at once.

[e] With copper wire coil; 1500 ampere turns.

tures. Of recent years we have interposed horizontal disks of asbestos ½ in. thick between the ends of the bar and the machine heads as shown in Fig. 9 on page 22. These disks are held between 6-in. cast steel flanges, the bolts of which are also insulated from contact with the flanges by asbestos winding. **Mr. Spring**

In many of our tests, the bottom of the hole which is drilled axially into the bar, as shown in Fig. 8 on page 21, contains two or three drops of metallic mercury to insure perfect contact of pyrometer tip with the bar itself. This eliminates any possibility of getting incorrect readings because of poor contact.

We have been using the gap wound coil, also shown in Fig. 8. With coils wound over their full length we found it almost impossible to avoid a higher temperature in the center of the breaking section of the test bar than at the ends. Part of this variation may be attributed to conduction or radiation of heat from the ends of the test bar. By using a coil with a 3-in. gap over the breaking section of a calibration bar drilled axially all the way down to the lower shoulder, the pyrometer tip showed very close temperature readings at lower shoulder, the center of the breaking section, and the upper shoulder where temperatures usually were taken.

MR. V. T. MALCOLM (*Author's closure*).—I have been very much interested in the various comments regarding the details of the test methods and in the several suggestions that have been made. Mr. Wilhelm is to be congratulated on the thoroughness of his work in this field of research. However, we must keep in mind that our tests must be as simple as possible because they are destined to become routine tests in the laboratories of the producers of high-temperature materials. In fact, this is true to some extent to-day; certain specifications now require that several test bars from each lot of steel of 200 lb. or over be tested at elevated temperatures. There is considerable difference between research and routine testing. For routine work apparatus must be developed that is accurate within certain limits and with which tests at elevated temperatures can be readily made. **Mr. Malcol**

In the entire discussion very little attention was given to the condition of the material before test. I believe this is one of the most important points to be taken into consideration if reliable results are to be obtained, for the reason that inclusions, gas pockets, segregation, etc., tend to give false results. The structural composition, both before and after testing at various temperatures, should be investigated, because we know that structural changes take place at elevated temperatures, especially in the non-ferrous materials. Elevated tem-

Mr. Malcolm. peratures, combined with corrosion or a cycle of normal temperatures, then elevated temperatures and back to normal, will give results quite different in service than with the use of elevated temperatures alone. Laboratory tests should be compared with actual service conditions and the results carefully studied and tabulated for use.

Mr. Lester's remarks regarding the X-ray method of test are quite pertinent. The writer is personally familiar with Mr. Lester's work, and is in a position to appreciate the value of the X-ray as applied to testing of steel.

Mr. Holz's references to certain apparatus and especially his remarks regarding routine testing are to the point and the writer hopes that he may have the opportunity of studying the methods described by Mr. Holz.

Mr. Marsh's discussion regarding temperature differences is one that is of vital interest to investigators carrying out this type of work, as the proper location of the thermocouple is of great importance in the reporting of reliable results and this is a matter for further study as well as the means of reaching thermal equilibrium so that there will be no doubt as to the correctness of the temperature of the material under test.

A point which has not been touched upon is the use of steel and a non-ferrous alloy together at elevated temperatures. The writer believes that this should be given careful consideration on account of the difference in the coefficients of expansion. For example, in a cast steel valve with a bronze seat ring, the difference in coefficients of expansion between steel and bronze at a temperature of 750° F. is so great as to cause the bronze ring to be stressed beyond its elastic limit and when the temperature returns to normal the ring would be loose and probably fall out. The improper application of some materials for services for which they are totally unsuited is the cause of a number of failures.

Mr. French. MR. H. J. FRENCH (*Author's closure*).—I think especially interesting is Mr. Hoyt's suggestion regarding the straight line relations between load and time of failure in metals. It may at some time clear up very readily for us, in tests made in the laboratory, some of the questions relating to practical service.

I would like for a moment to refer to points raised in presentation of Mr. Puffer's discussion. A question was asked regarding the machineability of the various heat-treated steels. Following the hardening operation, which we shall assume momentarily fully hardens the steel, it is necessary to temper at a temperature somewhat in excess of the service temperature for stability. If the steel is merely hardened and we then attempt to make use of it at high temperatures, say in the neighborhood of 1000° F. or above, the tempering will automatically take place in service and in many cases undesirable effects may be observed. The ordinary structural steels are of such a nature that a temperature of about 1000° F. or above will materially soften the alloy and leave it in a machineable condition. In the case of hardened high-speed steel somewhat higher tempering temperatures are necessary to effect this softening. Steels B1 and B2 of Fig. 8, referred to by Mr. Puffer, are not in an initially machineable condition. They have fair ductility, at least consistent with such high tensile strength values in ferrous alloys. These results were included only for comparison with the more complete data for annealed steels given in the same figure, and as already pointed out tensile strength values in short-time tests are not proper criteria for design purposes. **Mr. Frenc**

Reply to the question regarding the tensile properties at tempera-tured above 900° F. of a high-nickel-chromium steel similar to that in Fig. 14 may be found by referring to the Bibliography and the index to the Bibliography presented as a part of the Symposium.

The same applies to the last question having to do with the tensile properties of high-nickel-chromium alloys. However, it may be stated that we are now making a series of high temperature tests on a wide range of compositions in the nickel-chromium-iron series including both commercial and special alloys.

In reference to the remarks of Mr. Moss, it has already been mentioned that tempering subsequent to hardening must be carried out at temperatures at least equal to and generally above the proposed service temperature to produce stability. Attention should also be called to the fact that the weakening effects of high temperatures tend to diminish differences observed between different materials or treatments at ordinary temperatures. That, therefore, has a direct bearing on what we can do by varying hardening heats to produce exceptional properties in a given alloy. In other words by varying the hardening temperature and subsequent tempering we may produce very different results at ordinary temperatures but the necessity of tempering at or above the service temperature for stability and the weakening effects of temperatures in the neighborhood of 1000 to 1600° F., for example, limits materially what can be done by varying preliminary heat treatments. These features are more carefully discussed at some length on pages 57 and 62 of the paper on irons and steels.

Another point raised by Mr. Moss had to do with the time factor *versus* thermal equilibrium. I am not certain that I understand exactly

Mr. French. what he means by the thermal equilibrium, but both the papers presented and the discussion have thoroughly emphasized the importance of the time factor. In other words, there is no doubt that the time factor is important and that it is distinct from what I understand Mr. Moss to mean by thermal equilibrium.

I might in that connection repeat a very short item appearing on page 68, which is quoted directly from a very valuable report by Robin, as follows:

> "The properties of steel, so far as the dynamic and static effects are concerned, vary in totally different ways according to the temperature and according to the nature of the steels. The correlation of these effects at the normal temperature in the case of certain steels appears, therefore, to be due purely to coincidence."

I think that the work of Robin will possibly clear up this question with respect to thermal equilibrium and the time element.

Everyone must agree with Mr. Fahrenwald that the time factor is of great importance in any discussion of the high-temperature properties of metals and this has been emphasized in the paper on irons and steels. However, Mr. Fahrenwald is too optimistic and not in agreement with any of the other speakers in stating that "Much of the information that has been hoped for and suggested by the various authors of these papers has already been worked out and has been available for some years to the trade." It is not quite consistent with his later statement that "The problem of the application of metals and alloys at high temperatures is far more complicated and difficult than is ordinarily supposed."

Another subject which has been touched upon in the discussion is cast metals including so-called heat-resisting alloys but no one has mentioned or at least emphasized the importance of foundry practice in the production of these alloys.

We have recently tested some of the nickel-chromium-iron alloys and the uniformity of the results obtained from ostensibly the same lot of material has not been at all satisfactory. If I remember correctly, in one case at moderate temperatures, values of 75,000 lb. per sq. in. tensile strength were obtained, and the duplicate determination gave something like 50,000 lb. There were no visible flaws in the specimen to account for such a difference and the cause was not apparent offhand. This question of uniformity is of prime importance from several angles including the interpretation of test data. Numerical values given should not be used unless there is sufficient evidence that the stated properties can be uniformly produced in any product. While this is primarily a metallurgical problem, it affects materially the engineering application of these materials.

A. E. WHITE (*Author's closure*).—During this discussion three things seem to stand out. Mr. White.

The first relates to the need for information regarding the modulus of elasticity. That strikes me as an outstanding need. Very little work has been done upon it to date.

The second is the need for the development of a short-time test which will enable one to duplicate with a short-time test the changes resulting from long-time exposures to the given condition. I think the contribution of Mr. Hoyt, in which he mentions the possibility of plotting the logarithm of the time against the square root of the load, is a very valuable suggestion and one which should be given very careful consideration.

The third matter is the need for a suitable classification of metals and alloys. What are some of the outstanding metals which seem to enable an alloy to maintain its properties at elevated temperatures and what are the particular characteristics of these metals? On looking over the charts which have been prepared from the nonferrous data, it is noted that in the main when nickel is added to copper one gets decidedly beneficial effects. We might, therefore, make a statement that nickel seems to be beneficial to the extent of enabling metals to maintain their properties at elevated temperatures. If we will look over the data in the field of the ferrous metals, we will find that chromium is of decided benefit. We may, therefore, say that chromium is a metal of decided value from this standpoint.

We can, then, go a step further and think of an alloy of nickel and chromium. This alloy, of course, constitutes the base for most of our present-day heat-resisting alloys. Then we can go just a step further and ask what the particular properties are in chromium and nickel which enable these metals, when alloyed or by themselves, to undergo less change at elevated temperatures than most other metals and alloys. That gets us into the field of basic fundamentals. It is a field on which much important work is being done to-day. Everyone will appreciate that when the splendid fundamental work which is being done with regard to atomic structure is better understood and appreciated and when it is carried a bit further we will then be able to convert that information into our engineering needs so as to perfect a metal or an alloy which will approximate at elevated temperatures the properties it has at atmospheric temperatures.

CLOSURE BY COMMITTEE ON ARRANGEMENTS.—Measurable progress should be made from this Symposium, which has directed attention to many phases of the application and testing of metals at high and low temperatures. Already, definite results have been ob- Closure by Committee.

Closure by Committee.

tained, for it has (1) brought together widely scattered and important published information not in all cases readily accessible and likewise served to give a picture of the present state of our knowledge of the subject; (2) developed, through the general discussion, new data of value; and (3) focused attention upon the needs of industry and some of the most important problems to be solved separately or jointly by the metallurgist, chemist and engineer. It has, of course, been valuable in these respects and in promoting a widespread exchange of ideas, but of greater importance will be the future developments or what may be called the superstructure built upon the foundation of the Symposium.

As has been brought out in the Symposium, it is common knowledge that rather widely dissimilar results have been obtained by investigators in their tests of practically the same materials. This is not surprising, since they used different types of furnaces for heating the test pieces, different means of reading temperatures, various periods of time under heat, unlike speeds of loading, etc. It has become increasingly important that we know as accurately as possible the strengths of various engineering materials at elevated temperatures under approximate operating conditions. For this reason it is highly desirable that definite means be taken to determine the sources of error in the methods being used to-day and to determine upon a certain method or methods, which in the hands of investigators may be depended upon to give concordant results. Such methods when properly worked out and proved accurate, should be accepted as standard methods until superseded by other methods proved to be more accurate or advantageous.

In the belief that the time is now ripe for an organized and systematic effort along these lines, the Committee on Arrangements for the Symposium suggested the formation of a special committee under the joint auspices of the American Society of Mechanical Engineers and American Society for Testing Materials to foster and coordinate and possibly also to carry out service and laboratory investigations relating to the application and testing of metals at various temperatures.

[The above suggestion has met with the approval of the Executive Committee of the American Society for Testing Materials and the Council of the American Society of Mechanical Engineers, and plans are being made for the organization of a Joint Research Committee on the Properties of Metals at Extreme Temperatures.—ED.]